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REVIEW

A review of wave energy technology from a research and commercial perspective

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Abstract

Although wave energy prototypes have been proposed for more than 100 years, they have still not reached full commercialisation. The reasons for this are varied, but include the diversity of device operating principles, the variety of onshore/nearshore/offshore deployment possibilities, the diversity of the wave climate at various potential wave energy sites, and the consequent lack of convergence in technology and consensus. This distributed effort has, in turn, lead to a slow rate of progression up the learning curve, with a significant number of wave energy company liquidations and technical setbacks dampening investor confidence. Although a number of reviews on wave energy technology are already in the published literature, such a dynamic environment merits an up-to-date analysis and this review examines the wave energy landscape from a technological, research and commercial perspective.

1 | INTRODUCTION

'Carbon neutrality by 2050' is the world's most urgent mission, and António Guterres, the United Nations Secretary General, stressed on 11 December 2020 [1] that "By next month, countries representing more than 65 per cent of harmful greenhouse gasses and more than 70 per cent of the world economy will have committed to achieve net zero emissions by the middle of the century." To date, more than 110 countries have pledged to reach zero carbon emission by 2050. On the other hand, current energy demand mainly depends on fossil fuels, and is projected to rise by 1% per year until 2040 [2]. In the tension between global energy demand and carbon reduction promises, there exists a widening gap between rhetoric and action [3], and a significant transformation in the energy sector, with extra technical and non-technical efforts, is required to achieve carbon neutrality.

Among various renewable energy resources, wave energy shows great potential in bridging the gap between the rhetoric of carbon reduction and the increasing energy demand, being a relatively untapped resource, with the global wave resource in the range 1–10 TW. However, the exact global estimate of extractable wave power is debatable [4]. The theoretical estimate of global wave power is about 32,000 TWh/year (with a mean power of 3.65 TW) [4]. In terms of the usable wave power resource, excluding areas with wave power level < 5 kW/m, the global estimate is around 3 TW [5], while the mean wave power experienced by global oceanic coastlines is about 2.11 TW [6]. The assessment method and data in [5] are used by the Ocean Energy Systems (OES) and the International Renewable Energy Agency, with an estimate of 29,500 TWh/year [7, 8], which exceeds global electricity consumption in 2018, around 22,315 TWh with two-thirds mix from fossil fuels [9]. Together with other renewable resources, wave energy can play an import role in satisfying both the requirements of carbon emission reduction, and energy supply increase. Thus, OES member countries plan to achieve over 300 GW of installed wave/tidal capacity, create 680,000 direct jobs and save 500 Mt of carbon emission by 2050 [7].

Compared with other renewable resources, especially solar and wind power, the advantages of wave power are multiple: (i) Wave power is characterised by a high-energy density, over 10 times that of wind and solar power [10]. (ii) Wave power has a high availability, up to 90%, while the availability of wind and solar is generally in the range 20–30% [11]. (iii) Wave energy technology has little impact on the environment [12, 13]. (iv)

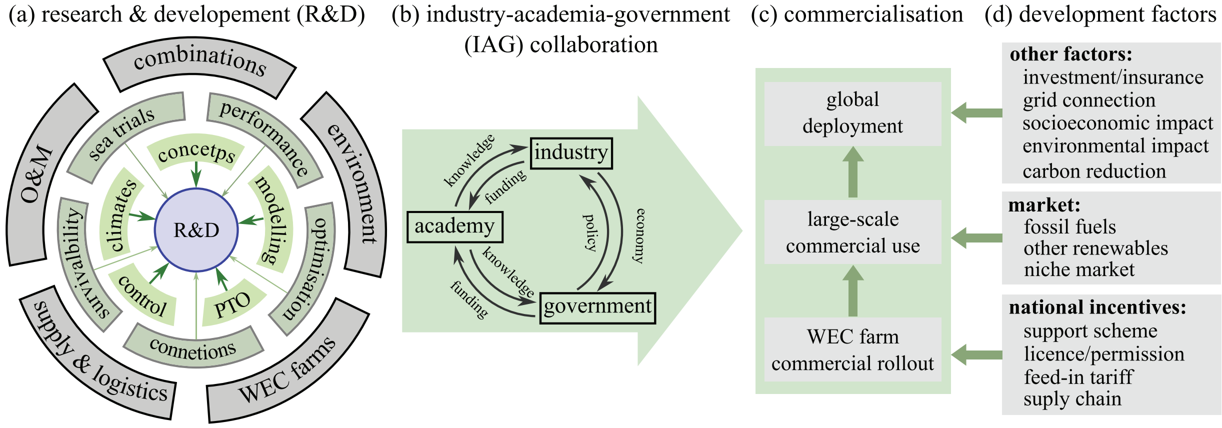

FIGURE 1 Possible pathway from WEC R&D activities to commercial deployment, with (a) R&D foci, (b) industry-academia-government collaboration, (b) commercialisation phases, and (d) critical development factors

Wave energy output can also be integrated with existing wind or solar power plants as a complementary resource for smoothing power output and reducing variability [14–19]. (v) Wave power is more predictable [20, 21], giving more flexibility for regional or national power management, and planning.

Despite the enormous potential of wave power, currently active wave capacity is as small as 2.31 MW [8, 22], and these operating wave energy projects are focused on research and demonstration. Currently, wave energy technology is at its 'infant' age, and there is no fully commercial scale wave energy converter (WEC) farm in operation, even though hundreds of WECs have been developed [23]. Crucially, there still exist several technical and non-technical challenges: (i) Technically, it is difficult to generate electricity from low-frequency (0.1 Hz, i.e., low velocity) oscillating motion and large force (1 MN). This requires extremely reliable structures and power take-off (PTO) systems and, consequently, high capital expenditure (CapEx). (ii) WECs operate in an offshore environment, with high installation, operation and maintenance costs. Thus, the operating expenditure (OpEx) is relatively large. (iii) The wave power resource varies on both a wave-by-wave, hour-by-hour, and site-by-site manner, in terms of wave frequency, height, direction, spectrum and power level, resulting in disparate WEC concepts without any convergence, diluting the efforts of research and development (R&D) and commercialisation. (iv) Extreme sea conditions occur from time to time, and the possibility of structural failure and device loss is relatively high. This adds extra risk for the finance sector to invest in WEC technology. (v) Currently, WEC technology is characterised by low maturity, high uncertainty and risk, and requires significant initial capital, which further discourages private investors. That is, diminishing private and public investments has been playing the most important recent role in advancing WEC technology by stimulating R&D activities.

In general, current WEC technologies or devices have not yet demonstrated their capability to harness enough wave energy at a low enough cost at commercial scale. Based on simplistic estimates of the levelised cost of energy (LCoE), some early stage WEC concepts, for example, the M4 device [24, 25], have showed their possibility to achieve a low LCoE for some specific installation sites. Further, geometric optimisation can improve WEC's hydrodynamic performance, in terms of power capture in moderate waves and survivability in extreme waves. On the other hand, sophisticated control approaches can significantly improve power capture, while marginally increasing the CapEx and, hence, dramatically reduce the LCoE [26]. However, WEC hydrodynamics and control are inherently and non-linearly coupled [27, 28], and a co-design approach is needed.

Current R&D activities mainly focus on wave resource assessment, WEC concept developing, hydrodynamic modelling, PTO innovation and control design. As shown in Figure 1(a), the topics in the inner ring are well studied, and plenty of reviews have summarised the state-of-the-art of wave resource assessment [16, 29–31], WEC technology [11, 32–38], modelling [38–47], PTO [11, 36, 48–50], and control [51–55]. The R&D topics in the middle and outer rings in Figure 1(a) are not fully understood yet. There are a few surveys summarising WEC survivability [56], performance [57], economic characteristics [58, 59], mooring [60] and shape optimisation [61, 62]. However, only a few studies aim to investigate critical development factors, as shown in Figure 1(c) and (d), for successful commercialisation of WEC technology at each phase [63–66].

In contrast to the aforementioned reviews, this review aims to discuss potential pathway of WEC commercialisation, from lab to market, by (i) summarising R&D activities in wave resource assessment, PTO innovation, WEC modelling and control, (ii) reviewing ongoing pre-commercial WEC demonstration projects, (iii) identifying potential market opportunities, including the utility market for electricity and niche markets related to ocean applications, and (iv) discussing industry-academia-government (IAG) collaboration to improve some critical development factors for bridging the valley of death (VoD) between R&D and commercialisation activities. WEC technology commercialisation relies not only on technical readiness level (TRL), but also on technical performance level (TPL), which attempts to measure the potential economic performance

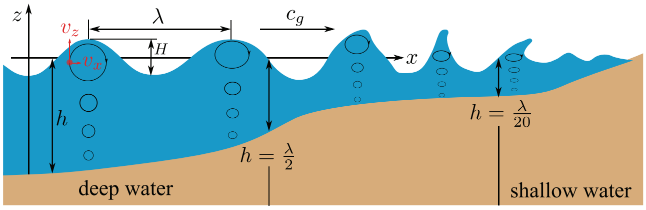

FIGURE 2 Wave from deep water to shallow water

of a wave energy device/project, and some external development factors, for example, investment environment, market data and national incentives. As the LCoE of WEC technology is still too high to compete with other renewable energy technologies, revenue and capital support from public sectors remains crucial [8]. Thus, public or government-related sectors play an important role in bringing together researchers and investors through support programs, market incentives, and regional policy and legislation, to form a solid IAG collaboration, as shown in Figure 1(b).

The reminder of the paper is organised as follows: Section 2 summarises the basic foundations of ocean waves and wave resource assessment, while Section 3 investigates various WEC concepts, classification, and modelling methods. Section 4 summarises the development of PTO systems and control strategies, with Section 5 examining possible development trajectories of a WEC prototype or project. Section 6 discusses historical and commercial efforts devoted to wave energy technology. Section 7 summaries potential market opportunists for WEC technology, while Section 8 identifies some key factors and incentives for commercialising WEC technology. Finally, some concluding remarks and future perspectives are drawn in Section 9.

2 | QUANTIFYING THE WAVE ENERGY RESOURCE

In ocean observation, the wave height H and period T can be directly measured. A simple illustration of wave propagating from deep water to shallow water is given in Figure 2. In Figure 2, h and λ are the water depth and wavelength, respectively. The shallow and deep waters are defined by $h \le \frac{\lambda}{20}$ and $h \ge \frac{\lambda}{2}$, respectively. As water depth decreases, the shallow water effect reshapes the wave profile, which may result in non-linear waves, wave breaking and energy loss [10, 67]. However, WECs normally operate in moderate sea states with $H \ll \lambda$. Thus, linear wave theory is normally valid and is applied in this section, with an overview of regular and irregular waves introduced with specific foci on quantifying the wave resource, its variability, and predictability.

2.1 | Regular waves and wave power

Swell waves, characterised by narrow bandwidth and relatively low frequency, are of primary interest for wave energy harvesting, and can be approximated by regular waves. In addition, calculations involving regular waves are relatively simple and can be used as a starting point for WEC R&D activities, particularly at low TRLs. For a regular (monochromatic) wave, the free surface elevation η, in Figure 2, can be written as

$$\eta(x,t) = \frac{H}{2}\cos(\omega t - kx + \varphi), \tag{1}$$

where $\omega = \frac{2\pi}{T}$, $k = \frac{2\pi}{\lambda}$ and φ are the wave frequency, wave number and initial wave phase, respectively. The wavelength can be determined by

$$\lambda = \frac{gT^2}{2\pi}\tanh(\frac{2\pi h}{\lambda}), \tag{2}$$

where g is the gravity constant. Alternatively, Equation (2) is generally rewritten as the dispersion relation, given as $\omega^2 = gk\tanh(kh)$. The group velocity of wave propagation in Figure 2 is expressed as

$$c_g = \frac{\lambda}{2T}\left[1 + \frac{2kh}{\sinh(2kh)}\right]. \tag{3}$$

The potential and kinetic wave energy per unit horizontal area are

$$E_p = E_k = \frac{\rho g}{2}\overline{\eta^2(x,t)}. \tag{4}$$

For regular waves, $\overline{\eta^2(x,t)} = \frac{H^2}{8}$ holds. Thus, total wave energy per horizontal area is given as

$$E = E_p + E_k = \frac{\rho g H^2}{8}. \tag{5}$$

Hence, the wave power per unit width of the wave front, J_r, also called wave-energy transport [68] or wave power level (used hereafter), is given as

$$J_r = c_g E = \frac{\rho g H^2}{8}\frac{gT}{4\pi}\tanh(kh)\left[1 + \frac{2kh}{\sinh(2kh)}\right], \tag{6}$$

Based on the deep-water assumption, the wave power level can be further simplified as $J_r \approx \frac{\rho g^2}{32\pi}H^2 T$.

2.2 | Irregular waves and wave power

In general, real waves are random and irregular, and can be approximated by the superposition of a group of sinusoidal waves as

$$\eta(x,t) = \sum_{i=1}^{N}\frac{H_i}{2}\cos(\omega_i t - k_i x + \varphi_i), \tag{7}$$

where H_i, ω_i, k_i and φ_i are the wave height, frequency, wave number and initial phase of the ith sinusoidal wave of N components, respectively. Based on linear wave theory, Equations (2)–(4) still hold. Thus, total wave energy power per horizontal area for irregular waves can be written as

$$E = \rho g \overline{\eta^2(x,t)} = \rho g \int_0^\infty S(\omega)\,\mathrm{d}\omega, \tag{8}$$

where $S(\omega)$ is the wave energy spectrum. Based on time-domain ocean observations, the wave spectrum can be estimated via FFT or spectrum estimation methods.

A variety of wave spectral models have been discussed in [67, 69], based on their application scenarios, pros and cons, of which the notable ones are the Pierson–Moskowitz (PM) [70] and joint North Sea wave project spectral models [71]. Here, the PM spectrum, generally used to describe fully developed wind waves, is taken as an example, given as

$$S(\omega) = \frac{5H_s^2}{16}\frac{\omega_p^4}{\omega^5}\exp\left(-\frac{5\omega_p^4}{4\omega^4}\right), \tag{9}$$

where H_s, $\omega_p = \frac{2\pi}{T_p}$ and T_p are the significant wave height, peak frequency and peak period, respectively. For a given wave spectrum, the significant wave height and energy period, T_e, can be estimated from spectral moments as

$$H_s = 4\sqrt{m_0}, \tag{10}$$

$$T_e = \frac{m_{-1}}{m_0}, \tag{11}$$

where m_i is the ith moment of the spectrum, given as

$$m_i = \int_0^\infty \omega^i S(\omega)\,\mathrm{d}\omega. \tag{12}$$

Thus, the wave power level for irregular waves can be written as

$$J = \frac{\rho g^2}{64\pi} T_e H_s^2. \tag{13}$$

2.3 | The global wave power resource and spatial variability

To estimate the wave resource over a large area, numerical wave models are generally used, of which the notable ones are the wave model, wavewatch 3, simulating waves nearshore, MIKE21-SW and TOMAWAC models, with their limitations and application scenarios discussed in [30, 31]. To achieve accurate wave resource assessment, observed wave data, at a set of discrete spatial points, are used to calibrate the models. Although the exact global estimate of extractable wave power is debatable, depending on assessment method, wave model, and temporal and spatial resolution, a small set of studies conclude that the applicable wave power in the world is about 3 TW by excluding areas of $J < 5$ kW/m [5, 7, 8]. Considering the area with 30 nautical miles to the coastline, extractable wave power decreases to 2.11 TW [6], and decreases further to 1.85 TW (approximating 16,000 TWh/year), when wave direction and coastline alignment are considered [4].

The wave power resource is evenly distributed between the Southern and Northern Hemispheres, as shown in Figure 3(a), but is concentrated within 30–60 degrees of latitude. Thus, latitude is one main factor affecting the spatial variability of the wave power resource. One typical example is the wave power resource along the Chilean coast, as shown in Figure 3(b), with the wave power level increasing from 20 to 100 kW/m, as the latitude increases from 15°S to 55°S. It also shows that water depth has some influence on the wave power level. As waves propagate to the coastline, the shallow water effect causes energy loss. Consequently, spatial variability has a significant influence on WEC performance [72, 74, 75]. As shown in Figure 3(c), the capacity factor of 3 WECs increases, as the latitude and wave power level increase. When wave power level is low, WECs should be scaled down accordingly to improve their performance [72, 75].

2.4 | Temporal variability and predictability of wave power

Wave power is characterised by significant temporal variability, ranging from seconds to decades. Such high temporal variability is one reason for the diversity of WEC concepts, and points to a required focus on WEC optimisation, PTO, control, survivability, power prediction, and management. Temporal variability can be classified into short-, medium- and long-term variations.

Short-term variation is characterised by irregularity in height, period and direction, varying from seconds to minutes. As the WEC control problem is typically non-causal, short-term prediction of wave elevation or excitation force is required, and prediction requirements for real-time control are investigated in [76]. Several prediction methods are discussed in [76–83], including the AR, ARMA, NARX and Bayesian learning methods. In addition, short-term variation results in a highly varying instantaneous wave power and a high peak-to-average power ratio, and extra design effort is required to smooth WEC harvested power, for example, PTO systems with accumulators/flywheels, to smooth high-frequency power variation.

Medium-term variation is represented by a change in wave spectrum or sea states, on an hourly or/and daily basis. Such variation may challenge the power management system of WEC farms, and accurate wave prediction over 1–72 h is required for power planning [16], and WEC installation and maintenance [83]. Compared with other renewable resources, wave power has an advantage in predictability [20, 21, 84], and the significant wave height can be accurately predicted in advance by a couple of days [16, 83, 85]. In addition, forming WEC arrays, or

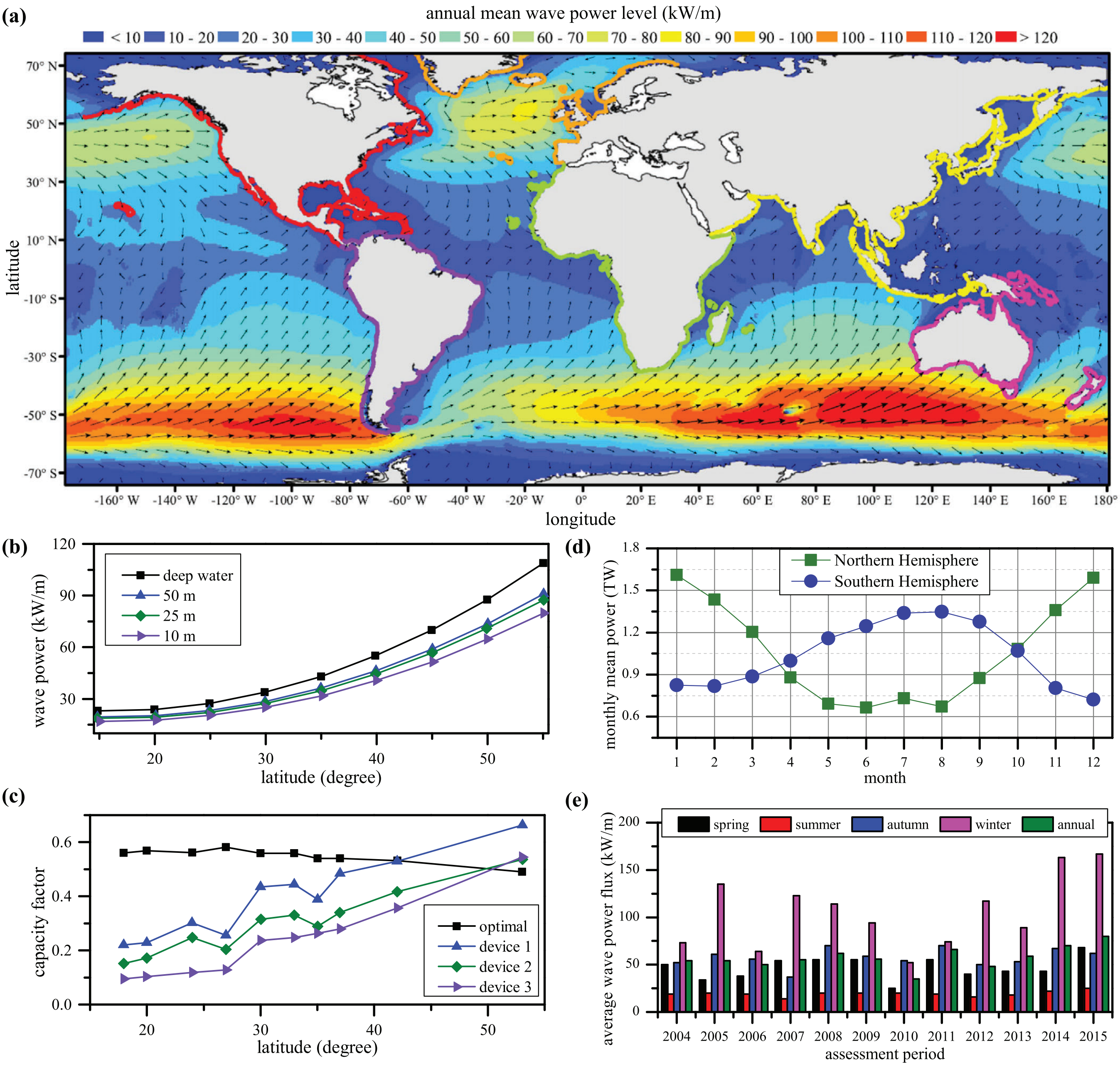

FIGURE 3 (a) Global wave resource distribution [6], (b) spatial variability along the Chilean coast, data from [72], (c) influence of wave power level variation and water depth on WEC capacity factor, data from [72], (d) monthly variability in the Northern and Southern Hemispheres, data from [6], and (e) seasonal and annual variability at the Atlantic Marine Energy Test Site, data from [73]

integrating WECs with wind turbines, can smooth power output to overcome medium-term variation [14].

Long-term variation concerns intra-annual and inter-annual variability of the wave power resource [4, 86–88]. Intra-annual variability includes monthly and seasonal variability, while the inter-annual variability refers to wave power variation over decades. In general, wave power is high in winter and low in summer, as shown in Figure 3(d) and (e). Inter-annual variability has a significant influence on lifetime performance of WEC farms and, thus, should be considered when determining deployment sites and design capacity ratings [87, 89, 90]. For instance, the wave power on the west coast of Ireland has seen a significant increase in the 20th century, which shows a power surplus of 15% within the lifespan of a point absorber (PA) or an oscillating wave surge converter (OWSC) [87, 91]. However, extreme events also increase, requiring more focus on WEC survivability [87]. In addition, increase in off-limit events ($H_s \geq 5$m) can significantly reduce the capture width ratio of an OWSC in the Irish sea, up to a level of 20% [92]. Thus, long-term trends of wave climate should be considered for commercial planning [29, 73]. However, long-term variability can, in general, be only hindcasted rather than forecasted [83].

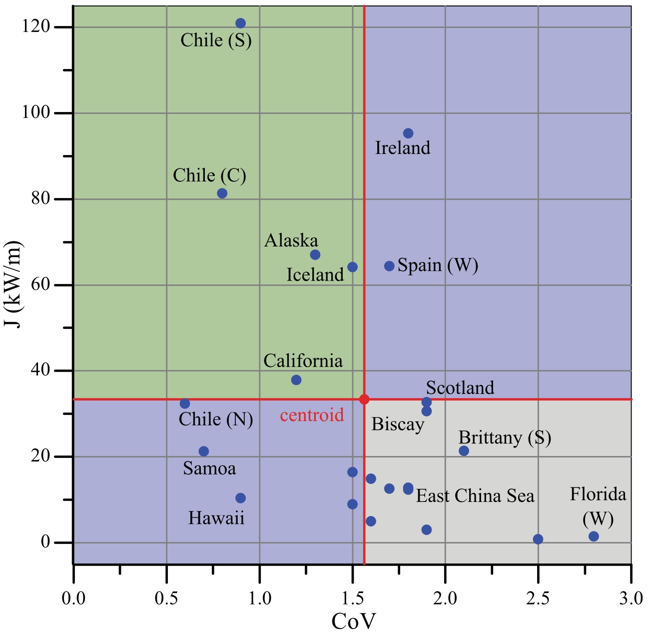

FIGURE 4 The average wave power level and the coefficient of variation for various typical sites, data from [94]. In this figure, the mean value for these sites is marked by the red dot; 'S', 'N', 'W', 'C' represent 'south', 'north', 'west' and 'central', respectively

Statistical methods are generally used to quantify the temporal variability of wave resource. One simple measure is the coefficient of variation (CoV) [93], given as

$$CoV(J) = \frac{\sqrt{\overline{\left(J(t) - \overline{J(t)}\right)^2}}}{\overline{J(t)}}, \tag{14}$$

where t is the time interval used for computing the wave power level J, ranging from 30 min to decades. Thus, the CoV can be used to describe medium- and long-term variability. Based on the CoV definition in Equation (14), a new world map for wave power with long-term variability is studied in [94], and shown in Figure 4. For various selected sites, the average value of (CoV, J) is marked by the red dot, which also divides Figure 4 into four regions. The sites in the green region (top left corner) are ideal for WEC installation, as the wave power level is high and the CoV is low.

Intra-annual variability can be quantified by the monthly variation index (MVI) and seasonal variation index (SVI) [93], while inter-annual variability is represented by the annual variation index (AVI) [86], as

$$MVI = \frac{J_{\mathrm{M,max}} - J_{\mathrm{M,min}}}{\overline{J_{\mathrm{Y}}}}, \tag{15}$$

$$SVI = \frac{J_{\mathrm{S,max}} - J_{\mathrm{S,min}}}{\overline{J_{\mathrm{Y}}}}, \tag{16}$$

$$AVI = \frac{J_{\mathrm{Y,max}} - J_{\mathrm{Y,min}}}{\overline{J_{\mathrm{Y}}}}, \tag{17}$$

where the suffixes M, S, and Y represent month, season and year, respectively, while the suffixes max and min represent maximum and minimum values, respectively. These measures are generally adapted to quantify temporal variability of wave power resource globally, regionally, and/or locally [4, 14, 16, 20, 29, 73, 86].

2.5 | Influence of wave climate on commercialisation

For commercialising WEC technology, the first step is to select a deployment site, mainly according to annual mean wave power level and temporal variability. Sites with a high wave power level but low variability are preferred, and WECs should be selected accordingly. Variation in wave climate is a strong cost driver in both CapEx and OpEx [94–96]. Short- and medium-term variability can be handled by real-time control and power management, along with wave climate prediction. However, long-term variability is difficult to forecast but can significantly affect the lifetime performance of WEC farms.

In addition, extreme wave conditions, characterised by maximum wave height and storm occurrence, have significant influence on accessibility and availability of wave power, and survivability of WEC devices. More R&D activities are needed to improve WEC survivability in extreme waves. To ease the installation and operation of WEC farms, other key factors should be considered, including water depth, distance to the coast, wind and tidal climate, existing infrastructure, and environmental and spatial constraints [89, 97].

3 | WAVE ENERGY TECHNOLOGY PRINCIPLES

This section gives an overview of working principles for various WEC concepts and their classification, followed by an overview of hydrodynamic modelling of WECs, based on these principles.

3.1 | Wave energy conversion concepts and classification

A WEC device converts the kinetic and/or potential energy contained in moving waves to useful energy (mainly electricity), comprising a set of floating or submerged bodies, a PTO unit, a control system, power electronics and other accessories. Since wave energy conversion concepts diverge, with over 1000 devices reported [10], there is no unique categorisation method to cover all possible WEC systems. In general, WECs can be classified according to their deployment locations, working principles, operation modes and device geometries [32, 34, 35, 38]. In this study, the classification method detailed in [35] is adapted and shown in Figure 5. In Figure 5, WECs are classified into three types, including oscillating water columns (OWCs), wave activated bodies and overtopping devices. For each type, the exemplified prototypes are pre-commercial and have been tested in the open ocean.

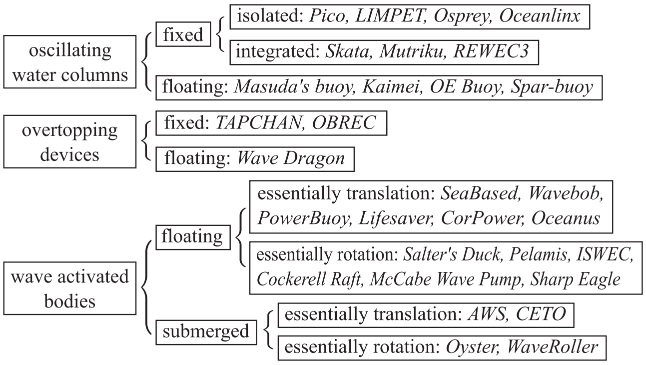

FIGURE 5 Classification of WEC devices, inspired by [35]

An OWC utilises a hollow structure with an open inlet below the still water level to trap air in its chamber above the inner free-surface; wave action alternately compresses and decompresses the trapped air, which forces air to flow through a turbine coupled to a generator [36], principally using the kinetic wave energy. As listed in Figure 5, OWCs can be further catalogued into two subclasses: (i) fixed OWCs, for example, the *Pico* and *LIMPET* devices, and (ii) floating OWCs, for example, Masuda's navigation buoy, and the *Spar-buoy* OWC. A comprehensive review, with a specific focus on OWCs and their PTO systems, is summarised in [36].

Overtopping devices are exemplified by fixed prototypes such as the *TAPCHAN* and *OBREC* devices, or the floating *Wave Dragon (WD)* device. Overtopping WECs mainly use potential wave energy, with electricity generated via somewhat conventional unidirectional (low head) hydro-turbines.

Most R&D activities focus on wave-activated WEC concepts, which can make use of the potential or/and kinetic wave energy to generate electricity [11, 35, 36, 62]. Wave-activated WECs can be further classified as (i) floating or submerged subclasses, according to wave-WEC interaction, (ii) rotating or translating subtypes according to the essential degrees of freedom (DoFs) exploited, or (iii) PAs, attenuators and terminators according to WEC geometry, with respect to wavelength and propagating direction. PAs refer to WEC devices whose characteristic dimensions are much smaller than the incident wavelength. PAs may operate in heave, pitch or multiple DoFs, and can be situated nearshore or offshore. Attenuators are floating WEC devices, oriented parallel to the wave direction, usually composed of multiple floating bodies connected by hinged joints, with relative motion between two connected bodies used to generate electricity via PTO systems. Terminators are oriented perpendicular to the wave direction, typically including duck-like devices, or OWSCs. Some typical wave-activated type WECs, at pre-commercial scales, are listed in Figure 5.

3.2 | Hydrodynamic modelling

Mathematical modelling of WEC dynamics gives a foundation for WEC R&D activities, and an accurate mathematical model

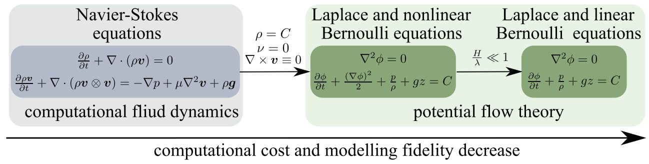

FIGURE 6 Governing equations for CFD and PFT

can be used for evaluating WEC performance, developing control strategies and optimising system design according to a specific wave climate. In the literature, a considerable amount of R&D activities have been devoted to WEC hydrodynamics, summarised in [38, 40, 41, 44–47, 98]. One main challenge of WEC modelling is how to represent the wave-structure interaction (WSI) in a proper way. Typically, the motion of a WEC structure is governed by Newton's 2nd Law, as

$$\boldsymbol{M}\ddot{\boldsymbol{\xi}}(t) = \boldsymbol{f}_{\mathrm{h}}(t) + \boldsymbol{f}_{\mathrm{g}}(t) + \boldsymbol{f}_{\mathrm{pto}}(t) + \boldsymbol{f}_{\mathrm{ext}}(t), \tag{18}$$

where $\boldsymbol{M}$ is the inertial matrix and $\boldsymbol{\xi}$ is the displacement of the WEC. $\boldsymbol{f}_{\mathrm{h}}$, $\boldsymbol{f}_{\mathrm{g}}$, $\boldsymbol{f}_{\mathrm{pto}}$ and $\boldsymbol{f}_{\mathrm{ext}}$ are the hydrodynamic, gravity, PTO (or control), and external forces, respectively. There is no unique representation of $\boldsymbol{f}_{\mathrm{ext}}$, but it may contain mooring and other potentially non-linear forces, for example, end-stop force [99–101]. Hydrodynamic fluid/body force can be computed as the integral of the pressure p on the wetted surface S, given as

$$\boldsymbol{f}_{\mathrm{h}} = -\iint_S p\,\boldsymbol{n}\,\mathrm{d}S, \tag{19}$$

where $\boldsymbol{n}$ is the normal vector on the wetted surface. Thus, the key of hydrodynamic modelling is to compute the pressure p in the fluid. Fluid dynamics is governed by the Navier–Stokes equations (NSEs), which cannot be solved analytically, and computational fluid dynamics (CFD) methods are generally applied to obtain a numerical solution. By assuming an ideal fluid (incompressible, inviscid and irrotational), the NSEs can be simplified to the Laplace and Bernoulli equations in Figure 6, and then solved using potential flow theory (PFT). With the pressure p obtained via CFD or PFT methods, the hydrodynamic force in Equation (19) can be computed.

CFD methods have been widely applied to provide high-fidelity numerical solutions to WSI, which can be classified into Eulerian and Lagrangian methods [44, 46]. Eulerian methods discretise the fluid into mesh elements, while Lagrangian approaches discretise the fluid as a set of particles. Eulerian-based CFD packages, for example, ANSYS Fluent, CFX, FLOW-3D, Star-CD/CCM+, and OpenFOAM, are generally used for modelling WEC dynamics, since they can handle all kinds of non-linear WEC hydrodynamics, for example, non-linear waves, turbulence, overtopping and slamming. On the other hand, Lagrangian-based smooth particle hydrodynamics (SPH) methods, for example, DualSPHysics [102], show advantages in automatic conservation of mass, and simplification of surface tracking, particularly suitable for extreme wave events, for example, wave breaking. However, SPH methods are not yet fully validated.

While providing high-fidelity modelling results, the computational cost of CFD approaches are expensive, with typically 10^4–10^5 seconds of computation (real) time for 1 s of simulation time [27, 103], significantly depending on CFD setups. By assuming sea water is ideal, fully non-linear potential flow (FNPF) theory can be used to solve the Laplace and non-linear Bernoulli equations in Figure 6, and compute the velocity potential function ϕ [44]. Thus, the pressure can be computed by

$$p = -\rho g z - \rho \frac{\partial \phi}{\partial t} - \frac{\rho}{2}(\nabla\phi)^2. \tag{20}$$

Currently, only a few software packages are based on the FNPF theory, for example, the high-order boundary element method of Ning *et al.* [104, 105]. Further assuming the wave height is much smaller than the wavelength ($H \ll \lambda$) and the device motion is small, linear potential flow (LPF) theory can be applied to solve the Laplace and linear Bernoulli equations in Figure 6. Thus, the total potential function can be divided into incident, diffracted and radiated components, as

$$\phi = \phi_{\rm i} + \phi_{\rm d} + \phi_{\rm r}. \tag{21}$$

For linear incident waves, an analytical solution of $\phi_{\rm i}$ generally exists. However, analytical solutions for $\phi_{\rm d}$ and $\phi_{\rm r}$ only exist for some simple WEC structures, for example, spheres and cylinders [106–108]. For arbitrary WEC geometries, mesh-based boundary element methods (BEMs) are generally used to obtain numerical approximations of $\phi_{\rm d}$ and $\phi_{\rm r}$. Common BEM solvers include WAMIT, NEMOH, AQWA, AQUA+ and WADAM in the frequency domain, and ACHIL3D in the time domain [47]. Substituting $\phi_{\rm i}$, $\phi_{\rm d}$ and $\phi_{\rm r}$ in Equations (20) and (21) and omitting the quadratic term in Equation (20), the pressure p is obtained, to allow the hydrodynamic force in Equation (19) to be computed.

In the time domain (TD), Equation (18) can be rewritten as Cummins' equation [109], given as

$$\begin{aligned} \boldsymbol{M}\ddot{\boldsymbol{\xi}}(t) &= \boldsymbol{k}_{\rm e}(\tau) * \boldsymbol{\eta}(t) + \left[-\boldsymbol{M}_\infty\ddot{\boldsymbol{\xi}}(t) - \boldsymbol{k}_{\rm r}(\tau) * \dot{\boldsymbol{\xi}}(t)\right] - \boldsymbol{K}\boldsymbol{\xi}(t) \\ &\quad + \boldsymbol{f}_{\rm pto}(t) + \boldsymbol{f}_{\rm ext}(t), \end{aligned} \tag{22}$$

where $\boldsymbol{f}_{\rm e}(t) = \boldsymbol{k}_{\rm e}(\tau) * \boldsymbol{\eta}(t)$ is the excitation force, as a sum of the Froude-Krylov (FK) and the diffraction forces, $\boldsymbol{f}_{\rm r}(t) = -\boldsymbol{M}_\infty\ddot{\boldsymbol{\xi}}(t) - \boldsymbol{k}_{\rm r}(\tau) * \dot{\boldsymbol{\xi}}(t)$ is the radiation force, and $\boldsymbol{f}_{\rm hs}(t) = -\boldsymbol{K}\boldsymbol{\xi}(t)$ is the hydrostatic force representing the balance between the gravity and buoyancy forces. $\boldsymbol{k}_{\rm e}(\tau)$, $\boldsymbol{M}_\infty$, $\boldsymbol{K}$ and $\boldsymbol{k}_{\rm r}(\tau)$ are the excitation kernel function, added mass at infinite frequency, restoring stiffness, and radiation kernel function, respectively. Alternatively, WEC dynamics can be written in the frequency domain (FD) as

$$\begin{aligned} \{-\omega^2[\boldsymbol{M} + \boldsymbol{M}_{\rm a}(\omega)] + j\omega\boldsymbol{B}(\boldsymbol{\omega}) + \boldsymbol{K}\}\Xi(\omega) \\ = \boldsymbol{K}_{\rm e}(\omega)A(\omega) + \boldsymbol{F}_{\rm pto}(\omega) + \boldsymbol{F}_{\rm ext}(\omega), \end{aligned} \tag{23}$$

where $\Xi(\omega)$, $A(\omega)$, $\boldsymbol{F}_{\rm e}(\omega) = \boldsymbol{k}_{\rm e}(\omega)A(\omega)$, $\boldsymbol{F}_{\rm r}(\omega) = [\omega^2\boldsymbol{M}_{\rm a} - j\omega\boldsymbol{B}]\Xi(\omega)$, $\boldsymbol{F}_{\rm pto}(\omega)$ and $\boldsymbol{F}_{\rm ext}(\omega)$ are the frequency-domain representations of $\boldsymbol{\xi}(\boldsymbol{t})$, $\eta(t)$, $\boldsymbol{f}_{\rm e}(t)$, $\boldsymbol{f}_{\rm r}(t)$, $\boldsymbol{f}_{\rm pto}(t)$ and $\boldsymbol{f}_{\rm ext}(t)$, respectively. $\boldsymbol{K}_{\rm e}(\omega)$, $\boldsymbol{M}_{\rm a}(\omega)$ and $\boldsymbol{B}(\boldsymbol{\omega})$ are the excitation frequency-response function, added mass and radiation damping, respectively.

The parameters, $\boldsymbol{K}_{\rm e}(\omega)$, $\boldsymbol{k}_{\rm e}(\tau)$, $\boldsymbol{M}_\infty$, $\boldsymbol{M}_{\boldsymbol{a}}(\boldsymbol{\omega})$, $\boldsymbol{k}_{\rm r}(\tau)$, $\boldsymbol{B}(\boldsymbol{\omega})$ and $\boldsymbol{K}$, can be obtained from the aforementioned BEM codes. The TD and FD models in Equations (22) and (23) can be connected according to Ogilvie's relations [110]. The TD and FD models can accurately depict WEC dynamics if the body motion is small. However, this is not always the case, especially when power maximisation control is applied to exaggerate WEC motion. In this case, some critical non-linear forces cannot be neglected any more, and hybrid modelling methods are generally applied to add some critical non-linear terms as treatments to $\boldsymbol{f}_{\rm ext}(t)$ in Equation (22).

By superimposing critical non-linear terms, a higher modelling fidelity can be achieved without a significant increase in computational cost. However, dominant non-linear factors depend significantly on specific WEC concepts, structure sizes, control strategies and application scenarios, and should be carefully considered on a case-by-case basis [42, 45, 111]. Depending on the additional non-linear term to $\boldsymbol{f}_{\rm ext}(t)$, hybrid modelling methods are divided into four types [47], including the body-exact, weak-scatterer, viscosity and mixed treatments.

The body-exact treatment considers instantaneous body motion when computing the FK, diffraction, radiation and restoring forces, covering large WEC motion. A critical aspect is the non-linear FK force, which has a large influence on WEC hydrodynamics [112–114]. The weak-scatterer treatment considers the instantaneous free surface while the wetted surface boundary condition is linearised at its mean value, allowing high-order potential functions for computing the pressure and hydrostatic force in Equations (19) and (20).

Fluid viscous effects can be represented by adding a quadratic drag term to Cummins' equation, via a Morison term [115], given as

$$\boldsymbol{f}_{\rm v} = \frac{1}{2}\rho C_{\rm d} A_{\rm s}(\boldsymbol{u} - \boldsymbol{v})|\boldsymbol{u} - \boldsymbol{v}|, \tag{24}$$

where $A_{\rm s}$ is the section area normal to the relative flow direction, $\boldsymbol{u}$ is the water particle velocity, and $\boldsymbol{v} = \dot{\boldsymbol{\xi}}$ represents the velocity vector of the WEC body. $C_{\rm d}$ is the viscous coefficient, depending on the Keulegan–Carpenter number, the Reynolds number and the roughness number [116]. Such a viscosity treatment can improve modelling accuracy significantly, especially for large relative fluid/body velocities. However, it is non-trivial to determine $C_{\rm d}$, and a wide range of wave conditions should be tested to obtain a consistent value [117–121]. To improve power capture, viscous effects should be minimised by geometric optimisation. For example, the M4 device utilises hemi-spherical bases to minimise viscous losses [24, 25].

The mixed treatment combines the viscosity representation with the body-exact or the weak-scatter treatments, leading to body-exact-viscosity or the weak-scatter-viscosity models. The former is more generally used for modelling WEC hydrodynamics, as controlled WECs are expected to oscillate with a large motion, even in moderate sea states [27, 47]. So, the body-exact-viscosity treatment is useful for modelling WEC dynamics in normal operation mode, where the modelling fidelity of a heaving PA, considering non-linear FK and viscous forces, can approach CFD results, with significantly lower computational cost [103].

Although the TD model in Equation (22) shows high flexibility in handling non-linear treatments, the excitation and radiation force convolution terms are not efficient for WEC R&D activities. Thus, system identification techniques are generally used to approximate the radiation convolution terms by finite-order parametrised models, for example, state-space models [122–127]. As the excitation kernel function $\boldsymbol{k}_e(\tau)$ is generally non-causal, extra effort is required to represent the excitation force [79, 81, 128–132]. More generally, system identification methods are applied to derive compact linear and non-linear models directly from CFD, or experimental, data [133–137].

3.3 | Influence of WEC technology on commercialisation

Dilution of R&D effort across many WEC concepts may be one main reason for currently low TRL and immaturity of WEC technology. To advance the convergence of WEC technology and concentration of R&D efforts, a common consensus on performance metrics for ocean energy technology is developing via international collaboration [66]. Hopefully, such a framework will accelerate the convergence of WEC technology, and consequently improve its TRL, maturity and commercialisation potential.

Hydrodynamic modelling of WECs has been well studied, but mainly for operational mode in moderate sea states. However, several WEC structural failures in storm conditions are reported in [138], even causing complete device loss. Recently, a few studies investigated WEC dynamics in extreme waves via tank testing [24, 25] or CFD simulation [56, 139, 140]. However, more research focus and effort on WEC dynamics in extreme waves are required to evaluate WEC survivability, reducing the risk of WEC commercialisation. Although there are some studies on the optimisation of WEC farm layout [141–145], only linear hydrodynamic models of WEC farm are typically used. For full commercial-scale WEC farms with tens of WEC devices, the interaction between WECs is not yet fully understood.

4 | POWER TAKE-OFF SYSTEM AND CONTROL

The PTO system is one key component of a WEC device, which transforms the mechanical power from the WEC motion to electricity. The PTO system has its own dynamics which, allied to those of the floater hydrodynamics, determines the overall frequency response characteristics of the system, which needs to be tuned to the relevant sea state via the control system. Consequently, a reliable and robust PTO, together with an appropriate control strategy, will improve commercialisation potential.

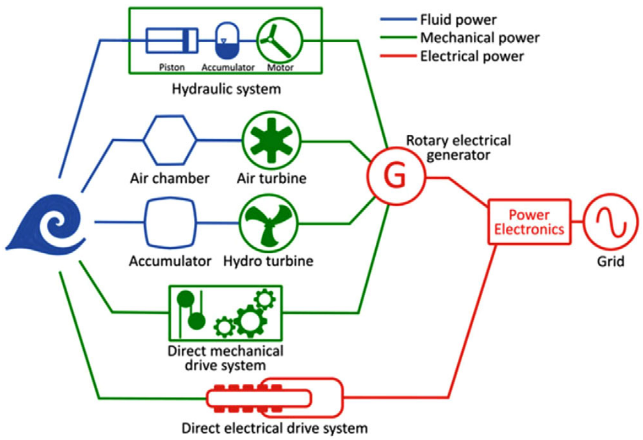

FIGURE 7 PTO systems for wave energy technology [160], courtesy of Professor Amélie Têtu

4.1 | Power take-off system

Various PTO systems are illustrated in Figure 7, including: (i) hydraulic PTOs, applicable to many kinds of WEC concept [49, 50, 146–152], (ii) air turbines for OWCs [36, 153], (iii) hydro turbines for overtopping devices [154], (iv) mechanical rectifiers [155, 156], and (v) direct-drive generators [157–159]. In general, these PTO systems are well modelled and market available, often derived from other application areas.

In general, PTOs cannot directly integrated to WEC devices, due to the following technical challenges: (i) PTOs are generally optimised to operate efficiently at a high unidirectional speed. However, WEC motion is typical slow, with mechanical rectifiers and mechanical or hydraulic gearing used to produce higher speed unidirectional motion. (ii) As discussed in Section 2, waves can have high temporal variability, making it difficult to determine the rated specifications for PTO components. In addition, short-term variability induces a high peak-to-average power ratio, which may lead to occasional overrated conditions. Thus, PTOs which can operate efficiently over a wide range of sea states are required. (iii) Extreme sea state occurs occasionally, exceeding the PTO physical constraints, for example, maximum stroke, velocity, force and power, so PTO decoupling mechanisms are required.

Current WEC modelling tends to assume that PTOs in Figure 7 are ideal, simplified the model to a mass-spring-damper system, or neglecting some important non-linear factors, for example, hysteresis effect [148], dead-zone, saturation, friction [151], and load effects [161]. This may lead to incorrect design decisions regarding the PTO and control systems. For high-fidelity PTO modelling, both their dynamics and efficiency variations with load should be considered. In general, the average efficiency of a non-ideal PTO deceases as the reactance/resistance ratio increases [161], and the average PTO efficiency decreases dramatically when the load diverges from its rated value. A large amount of energy will also be dissipated by non-ideal PTOs, in terms of hydraulic leakage [152], mechanical loss [151, 152, 155], or copper loss [162–164]. Thus, non-linear and non-ideal PTO factors should be modelled and then considered at the control design stage.

Since PTOs are naturally non-ideal and non-linear, it is more realistic to integrate a non-linear PTO model with a non-linear WSI model to form a high-fidelity wave-to-wire (W2W) model for control, optimisation and performance evaluation [43, 45, 54, 165]. However, such a model is complex and expensive in computation. Thus, systematic complexity reduction approaches are required to achieve an acceptable balance between fast computing and model fidelity, discussed in [164, 166, 167].

4.2 | Control

Since ocean waves are irregular in amplitude and frequency, and sea states change all the time, control approaches are required by WECs for power maximisation in mild/moderate waves and survivability enhancement in extreme waves. A wide range of WEC control strategies are available, for example, reactive control [168], phase control [68], optimisation-based control [53], adaptive control [169, 170]. This section only discusses some basic concepts of WEC control, major milestones in the literature, and their influence on WEC commercialisation. Detailed control reviews are given in [51, 53–55].

4.2.1 | Classical control strategy

The fundamental (classical) study of power maximising control of WEC systems dates back to 1975 [168], which is based on monochromatic waves, linear hydrodynamics and an ideal PTO. To derive optimal conditions, Cummins' equation in Equation (23) can be rewritten as

$$\frac{\boldsymbol{V}(\omega)}{\boldsymbol{F}_{\mathrm{e}}(\omega)+\boldsymbol{F}_{\mathrm{pto}}(\omega)}=\frac{1}{\boldsymbol{Z}_{\mathrm{i}}(\omega)}, \tag{25}$$

where $\boldsymbol{V}(\omega)$ represents the body velocity in the frequency domain. $\boldsymbol{Z}_{\mathrm{i}}(\omega)$ is the intrinsic impedance of the system, given as

$$\boldsymbol{Z}_{\mathrm{i}}(\omega)=\boldsymbol{B}(\omega)+j\omega\left[\boldsymbol{M}+\boldsymbol{M}_{\mathrm{a}}(\omega)-\boldsymbol{K}/\omega^{2}\right]. \tag{26}$$

According to the maximum power transfer theorem, the optimal PTO system should satisfy

$$\boldsymbol{Z}_{\mathrm{pto}}(\omega)=\boldsymbol{Z}_{\mathrm{i}}^{*}(\omega). \tag{27}$$

Thus, the absorbed power is maximised when the PTO impedance is the complex conjugate of the system intrinsic impedance, so-called complex-conjugate control, or reactive control (RC) [68], with bidirectional power flow required in

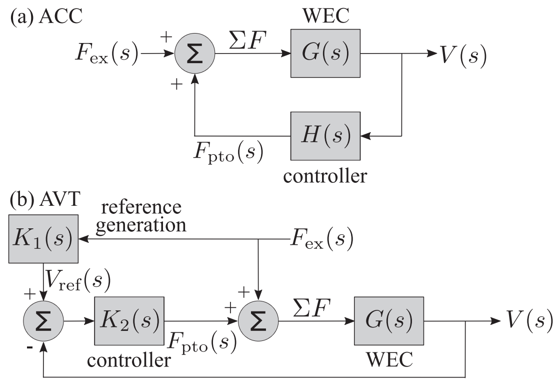

FIGURE 8 (a) Approximate complex conjugate (ACC) and (b) approximate velocity tracking (AVT) control frameworks [55]

Equation (27). With some PTOs only allowing uni-directional power flow, for example, dampers, RC degenerates to so-called passive control (PC), as $\boldsymbol{B}_{\mathrm{pto}}(\omega)=|\boldsymbol{Z}_{\mathrm{i}}(\omega)|$.

For RC in Equation (27), the optimal velocity is written as

$$\boldsymbol{V}_{\mathrm{opt}}(\omega)=\frac{\boldsymbol{F}_{\mathrm{e}}(\omega)}{2\boldsymbol{B}(\omega)}, \tag{28}$$

which indicates that the absorbed power is maximised if the amplitude and phase conditions,

$$|\boldsymbol{V}_{\mathrm{opt}}(\omega)|=\frac{|\boldsymbol{F}_{\mathrm{e}}(\omega)|}{2|\boldsymbol{B}(\omega)|}\ \text{and}\ \boldsymbol{V}_{\mathrm{opt}}(\omega)=\frac{\boldsymbol{F}_{\mathrm{e}}(\omega)}{2\boldsymbol{B}(\omega)},$$

are simultaneously satisfied. For a given frequency, the amplitude condition can be achieved by selecting a suitable damper, while the phase condition can be achieved by latching control (LC) [68] or declutching control (DC) [171].

In addition to strong assumptions of monochromatic wave, linear hydrodynamics and ideal PTO, physical constraints, for example, WEC stroke, cannot be easily handled by classical control strategies and, thus, their value is limited. However, Equations (26)–(28) have established the theoretical foundation for WEC control.

4.2.2 | Modern control strategies

Ocean waves are generally panchromatic, and the optimal control laws in Equations (26)–(28) can be extended to the approximate complex-conjugate (ACC) and approximate velocity tracking (AVT) structures [55], respectively, as shown in Figure 8. The ACC structure, which is optimal only for the predominant wave frequency, does not require any estimation or forecasting of wave excitation force, but cannot handle constraints directly, and hard to improve its robustness to modelling errors [172]. Meanwhile, the AVT framework is more flexible than the ACC one, permitting the incorporation of physical constraints, and is generally used for the majority of optimal control strategies, but requires knowledge of the excitation force, and is significantly more computationally complex.

In general, the WEC control problem can be rewritten as an optimal control problem, given as

$$\min_{\boldsymbol{f}_{\text{pto}}} - \int_0^T \boldsymbol{f}_{\text{pto}}(t)\,\boldsymbol{v}(t)\,\mathrm{d}t$$
$$\text{s.t.}\boldsymbol{\xi}(t) \le \boldsymbol{\xi}_{\max},$$
$$\boldsymbol{f}_{\text{pto}}(t) \le \boldsymbol{f}_{\max}, \tag{29}$$

where $\boldsymbol{\xi}_{\max}$ and $\boldsymbol{f}_{\max}$ are the PTO constraints in stroke and force, respectively. Based on this formulation, several optimal control algorithms are summarised in [53]. Among various optimal control approaches, model predictive control (MPC) is widely investigated, for linear hydrodynamics [173, 174], non-linear hydrodynamics [175], non-ideal PTO [162, 176], and even WEC arrays [177].

Numerical optimisation in Equation (29) is time consuming, which may cause some difficulty in real-time implementation. In addition, the WSI is so complex that the convexity of Equation (29) is not generally guaranteed. Further considering physical constraints in WEC stroke and PTO force, the existence of optimal control solutions is also not guaranteed. Once wave excitation exceeds a certain level, there may be no control solution that simultaneously satisfies PTO constraints in force and displacement [55, 178]. Thus, the existence of an optimal solution depends on wave conditions, WSI and the PTO specification. On the other hand, a well-controlled WEC tends to oscillate significantly, resulting in large body motion which, in turn, exaggerates non-linear hydrodynamics [27, 28]. Thus, control should be considered in WSI and PTO modelling, requiring a relatively high-fidelity W2W model, inherently considering non-linear WSI and non-ideal PTO. However, such a model is typically complex, and systematic complexity reduction is inevitable [164, 166, 167].

4.2.3 | New trends in control

To advance WEC control implementation, recent R&D efforts have been devoted to robust control, model-free control (MFC), and system complexity reduction.

Since WSI is somewhat of a 'blackbox', modelling error and uncertainty are inevitable. Thus, control strategies have been designed to address the robustness to: modelling error [80, 179–183], external disturbance [184–186], and estimation/prediction error of excitation force [187]. Model sensitivity issue for different WEC control system architectures is analytically and numerically studied in [172], revealing that the AVT architecture is relatively insensitive to inertial and stiffness terms, and generally has superior robustness compared with the ACC framework [172].

MFC is an alternative to robust control, aiming to make WEC performance more immune to model uncertainty, external perturbation and unmodelled dynamics. Among various MFC control methods, some notable examples are extremum-seeking algorithms [188], artificial neural networks [189], deep reinforced learning control [190], machine learning [191], least-squares policy iteration [192] and adaptive control [170]. Some of these MFC methods inherently contain a large number of optimisation iterations, resulting in real-time implementation challenges.

A high-fidelity W2W model, with non-linear WSI and non-ideal PTO, is naturally complex, with complexity reduction required for control and optimisation [43, 45, 54, 165]. For real-time implementation, an interesting aspect is to avoid some of the particular problems, including (i) excitation force estimation, (ii) excitation force forecasting, and (iii) numerical optimisation [55].

4.3 | Influence of PTO and control on commercialisation

For advancing PTO designs and implementation, R&D activities should use a realistic and non-ideal model for numerical investigations in modelling, performance evaluation, control development and design optimisation. For practical testing, attention should be paid to PTO optimisation with respect to wave climate, to improve its reliability for long-term operation. In addition, a durable PTO should have a decoupling design to survive in extreme waves.

Control plays the most important role in advancing WEC economic performance by reducing LCoE. Although WEC controllers increase CapEx by a small margin, annual energy production can be improved significantly. A typical example is the *SEAREV G21* device [26], where a properly designed control system increases the annual energy production from 730 MWh to 1300 MWh, with the CapEX only increasing from 5 M€ to 5.3 M€. In general, hydrodynamics, PTO dynamics and control are inherently coupled in a non-linear manner, and such a coupling is not yet fully understood [27, 28]. Thus, it is imperative to establish a co-design framework to accurately address such a coupling in its true form.

Supervisory control, to switch WEC system between operation and survival modes according to sea sates, and fault tolerant control, to improve system reliability, are seldom tackled. Several studies have addressed the array control problem [193–197], but are limited to small device numbers and simple array layouts.

5 | WEC DEVELOPMENT TRAJECTORIES

To take a high-tech product from lab to market, it is critical to evaluate the maturity of the technology, mainly represented by TRL. However, a successful commercial strategy also requires that the technology is marketable and investable, represented by TPL. Based on a TRL-TPL-matrix, it is possible to find an ideal development trajectory for WEC projects, even at very early development stages. To date, some WEC projects have achieved either high TRL or TPL. However, high TRL and TPL do not naturally indicate successful commercialisation, and many new ventures have failed to bridge the VoD. In this section, the development trajectory of R&D WEC projects will be discussed

TABLE 1 Characteristics of functional readiness and lifecycle readiness for TRLs, adapted from [198]

TRL	Function readiness	Lifecycle readiness
1	Basic principles observed and reported.	Potential uses of technology identified.
2	Technology concept formulated.	Market and purpose of technology identified.
3	Analytical/experimental key function and/or characteristic proof-of-concept (**scale < 1:25**).	Initial capital cost and power production estimates or targets established.
4	Technology component and/or basic technology subsystem validation in a laboratory environment (**scale > 1:25**).	Preliminary lifecycle design: targets for manufacturable, deployable, operable, and maintainable technology.
5	Technology component and/or basic technology subsystem validation in a relevant environment (**scale > 1:15**).	Supply-chain mobilisation: procurement of subsystem design, installation feasibility studies, cost estimations, etc.
6	Technology system prototype demonstration in a relevant environment (**scale > 1:4**).	Customer interaction: consider customer requirements to inform type design. Inform customer of likely project site constraints.
7	Technology system prototype demonstration in an operational environment (**scale > 1:2**).	Ocean operational readiness: management of ocean scale risks, marine operations, etc.
8	Actual product completed and qualified through test and demonstration (**full scale, 1 device**).	Actual marine operations completed and qualified through test and demonstration.
9	Operational performance and reliability demonstrated for an array of type machines (**3–5 devices**).	Fully de-risked business plan for utility-scale deployment of arrays.

in the TRL–TPL space, together with potential measures to bridge the VoD for new ventures.

5.1 | Technology readiness level

TRL was initially developed by NASA to estimate the maturity of a technology of high risk, novelty and complexity, for example, for space programmes. For WEC technology, the technology readiness assessment is tailored by Fitzgerald and Bolund [198], in the categories of functional readiness and lifecycle readiness, as shown in Table 1. Functional readiness is more commonly used than lifecycle readiness, as there only exists very limited experience of long-term WEC operation. Hereafter, TRL refers to the functional readiness only. Table 1 clearly shows that TRL significantly relates to the scale ratio, mainly according to the Froude number, with successful demonstration of a small WEC array at TRL 9 indicating that the technology is mature, or ready for commercialisation.

A WEC development roadmap, from design to commercialisation, is also discussed in [199], with specific foci on TRL-related development activities and assessment criteria for single WECs and WEC farms. By summarising existing R&D WEC projects, the WEC development plan (in 2010) is divided into five stages [200] and six stages in 2021 [66], aiming to comprise the best practices and recommended procedures for wave energy technology. One big lesson learnt for the TRL-roadmap in [200] is that the development cost and time are high, as shown in Figure 9(a).

5.2 | Technology performance level

Since TRL was initially used for the NASA space program, development cost and time are not as important as technology maturity. However, this is not the case for WEC technology. Marketability and affordability are as important as technology maturity, which are not considered in the TRL assessment of Table 1. Thus, the concept of TPL was proposed by Weber [201, 202], to address the importance of technology performance, power capability, system availability, CapEx and OpEx. The characteristics and categories of each TPL level are detailed in Table 2. To assess TPL at early stages of WEC projects, guidance is given in [203].

With more emphasis on LCoE drivers, an updated TPL assessment method was used for the Wave Energy Prize [204]. For successful WEC commercialisation, stakeholder requirements on WEC technology are identified in [64], as: (i) having market-competitive cost of energy, (ii) providing a secure investment opportunity, (iii) being reliable for grid operations, (iv) benefiting society, (v) being acceptable to permitting and certification; (vi) being safe, and (vii) being deployable globally. A third TPL assessment update is provided in [205], where TPLs can be applied to all TRLs and development stages of WEC devices and farms. At low TRL, TPL assessment is very effective, as it considers a wide range of techno-economic performance criteria. At high TRLs, TPL assessment is more strict. More detailed methods to score TPL is given in [206].

5.3 | Development trajectory

Based on TRL and TPL assessment, a TRL-TPL matrix is established in [65, 202], to discuss possible development trajectories for a WEC project. Intuitively, there are two simple development trajectories: the TRL-first trajectory (blue curve) and the TPL-first trajectory (green curve), as shown in Figure 9(b). The TRL-first trajectory is conventionally used in WEC development, where WEC development concentrates on improving the TRL first, and then attempts to improve TPL at a high TRL. In contrast, the TPL-first trajectory prioritises TPL over TRL by evaluating WEC techno-economic

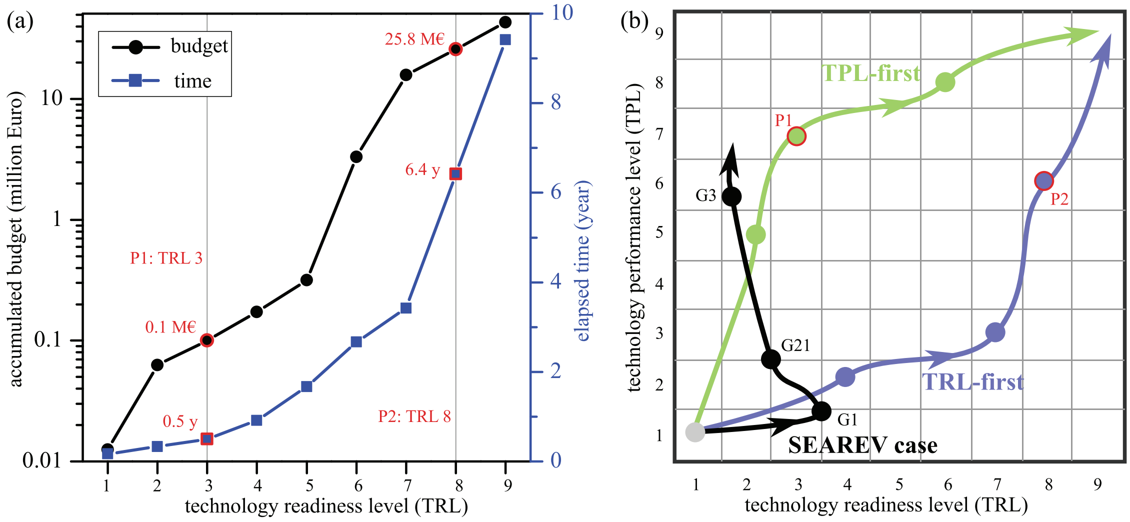

FIGURE 9 (a) WEC development cost and elapsed time evolution as TRL increases from 1 to 9, data from [200], and (b) potential WEC development trajectories in the TRL-TPL-matrix. In (a), the mean values of development cost and elapsed time are used. In (b), the development trajectory of the *SEAREV* device is adapted from [26]. The markers P1 and P2 show the development cost and elapsed time at TRL levels of 3 and 8, respectively

TABLE 2 Characteristics and categorise of TPLs, adapted from [202]

TPL	Characteristics	Category
1	Majority of key performance characteristics and cost drivers do not satisfy and present a barrier to potential economic viability.	**High**: Technology is economically viable and competitive as a renewable energy form.
2	Some of key performance characteristics and cost drivers do not satisfy potential economic viability.	
3	Minority of key performance characteristics and cost drivers do not satisfy potential economic viability.	
4	In order to achieve economical viability under distinctive and favourable market and operational conditions, some key technology implementation and fundamental conceptual improvements are required.	**Medium**: Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological or conceptual improvements may be required.
5	In order to achieve economic viability under distinctive and favourable market and operational conditions, some key technology implementation improvements are required.	
6	Majority of key performance characteristics and cost drivers satisfy potential economic viability under distinctive and favourable market and operational conditions.	
7	Competitive with other renewable energy sources given favourable support mechanism.	**Low**: Technology is not economically viable.
8	Competitive with other energy sources given sustainable support mechanism.	
9	Competitive with other energy sources without special support mechanism.	

performance at low TRLs, with significantly lower design cost implications. In addition, another combined trajectory is discussed also in [65], and demonstrated well by the *SEAREV* case study [26], shown as the black curve in Figure 9(b). The first generation device, *SEAREV G1*, reaches (TRL,TPL)=(4,2), but its LCoE is high. Shape optimisation and control are implemented for the second-generation device, *SEAREV G21*, at (TRL,TPL)=(3,3). Further design optimisation for the third-generation device, *SEAREV G3*, prioritises TPL over TRL, arriving at (TRL,TPL)=(2,6).

The traditional TRL-first trajectory requires several technology steps at full technology readiness. Development costs, and time required for each TRL, are estimated in [200], and the mean values are illustrated in Figure 9(a). As the TRL increases from 3 to 8 (see the points P1 and P2), the accumulated budget and time increase from 0.1 M€ to 25.8 M€ and from 0.5 years to 6.4 years, respectively. By projecting P1 and P2 to the TPL-first and TRL-first trajectories in Figure 9(b), respectively, it is clear that the TPL-first trajectory is significantly cheaper in achieving a high TPL [202]. A comparison study of the TRL-first, TPL-first, and combined trajectories in [65] strongly recommends the TPL-first trajectory, as the other requires double the development time and cost, and is more prone to project failure. Based on the TRL concept, a framework for evaluating WEC

TABLE 3 WEC development stages based on TRLs, inspired by [66]

Stage	TRL	Verification
0: Concept creation	1	Analytical and numerical models
1: Concept development	2–3	
2: Design optimisation	4	Experimental tests in controlled environment
3: Scaled demonstration	5–6	
4: Commercial-scale single device demonstration	7–8	Experimental tests in representative environment
5: Commercial-scale array demonstration	9	

performance, and a development process, is identified in [66]. Within this framework, the WEC development process is divided into six TRL-related stages, given in Table 3. For each stage, technology performance is evaluated in terms of power capture, power conversion, controllability, reliability, survivability, maintainability, installation ability, manufacturability, and affordability, to define evaluation criteria, methods, thresholds, activities and stage entry requirements. R&D projects should proceed further to the next TRL-based stage only when all stage gate metrics are met.

In the TRL-TPL matrix, market entry conditions are defined as (TRL,TPL)=(9,>7) [202]. However, this does not indicate successful commercialisation. According to the commercial readiness index (CMI) defined in [207, 208], market-entry WEC technology only arrives at the commercial trial stage, far away from successful commercialisation.

5.4 | Valley of death

The VoD, for WEC commercialisation, is referred to as the period in which a startup venture begins to develop products for early commercial trial, but has not yet brought in revenue from market. As shown in Figure 10, the VoD refers to the negative cash flow gap between R&D activities to early commercialisation. In this study, cash flow (CF) [63] is defined as

$$CF(y) = \frac{Rev(y) - CapEx(y) - OpEx(y) - Tax(y)}{\left(1 + \frac{R_d}{100}\right)^y}, \quad (30)$$

where *Rev*, *CapEx*, *OpEx* and *Tax* are the annual revenue, capital expenditure, operation and maintenance expenditure, and annual taxes, respectively. R_d and y are the discount rate and the year index, respectively, with the life-cycle running from y_0 to Y.

In Figure 10, basic success is represented by the black curve, where a positive CF is achieved at the end of commercialisation. For some specific WEC projects or devices, failure may occur before operation or generation of any revenue (see the red curve), mainly due to a low TPL, for example, low in manufacturability, installability or grid accessibility. After successful commissioning, a WEC project starts to operate, generating elec-

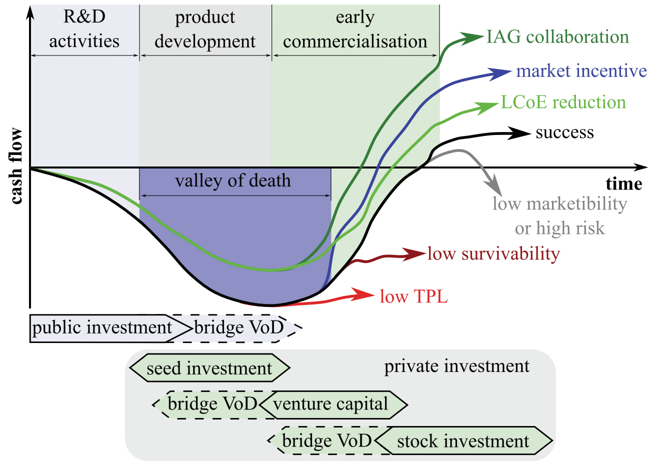

FIGURE 10 The cash flow valley of death

tricity, and bringing revenue. Still, commercialisation may fail if the deployed WEC technology is of low survivability, shown by the brownish red curve. WEC devices may also be destroyed by extreme waves conditions, for example, storms. Another big concern is marketability. Even though a positive CF is achieved, project failure may still occur (see the grey curve) if the LCoE from wave is not as competitive as other renewable energy technologies. Such a failure may be caused by frequently required maintenance, disappearance of feed-in tariff (FIT), or a dramatic reduction in the LCoE of other renewable energy technologies.

To successfully commercialise wave energy technology, the IAG collaboration plays the major role to bridge the VoD. Technically, novel WEC concepts, PTO innovation and robust control show great potential in LCoE reduction. In addition, the TPL-first development trajectory can further reduce the LCoE by saving development cost and time, and mitigating development risk. With these technical measures, the black CF curve can be raised to the green curve, thus relieving the dearth of investment during the VoD. On the other hand, market incentives from government-related sectors, like FIT, can benefit revenue and CF directly, lifting the black curve to the blue one. FITs have a significant influence on overall WEC economic performance [63], and an appropriate FIT rate can even drive a defective commercial project into a profitable one. Beyond market incentives, government-related sectors can further develop regional and national strategies to reinforce IAG collaboration, to achieve a significant commercial success, shown as the dark green curve in Figure 10.

To bridge the VoD via IAG collaboration, public or government-related sectors play a most important role to bring together researchers and investors, by developing national strategies and using market incentives, even at the early stage of a specific WEC technology for better two-way knowledge transfer and communication [8, 209]. Current national strategies and market incentives are discussed in Section 8. Given that the development and commercialisation of WEC technology require significant time and funding levels, and are of high risk, public investment should be prolonged even after market entry, to mitigate investment risk by building sea test sites,

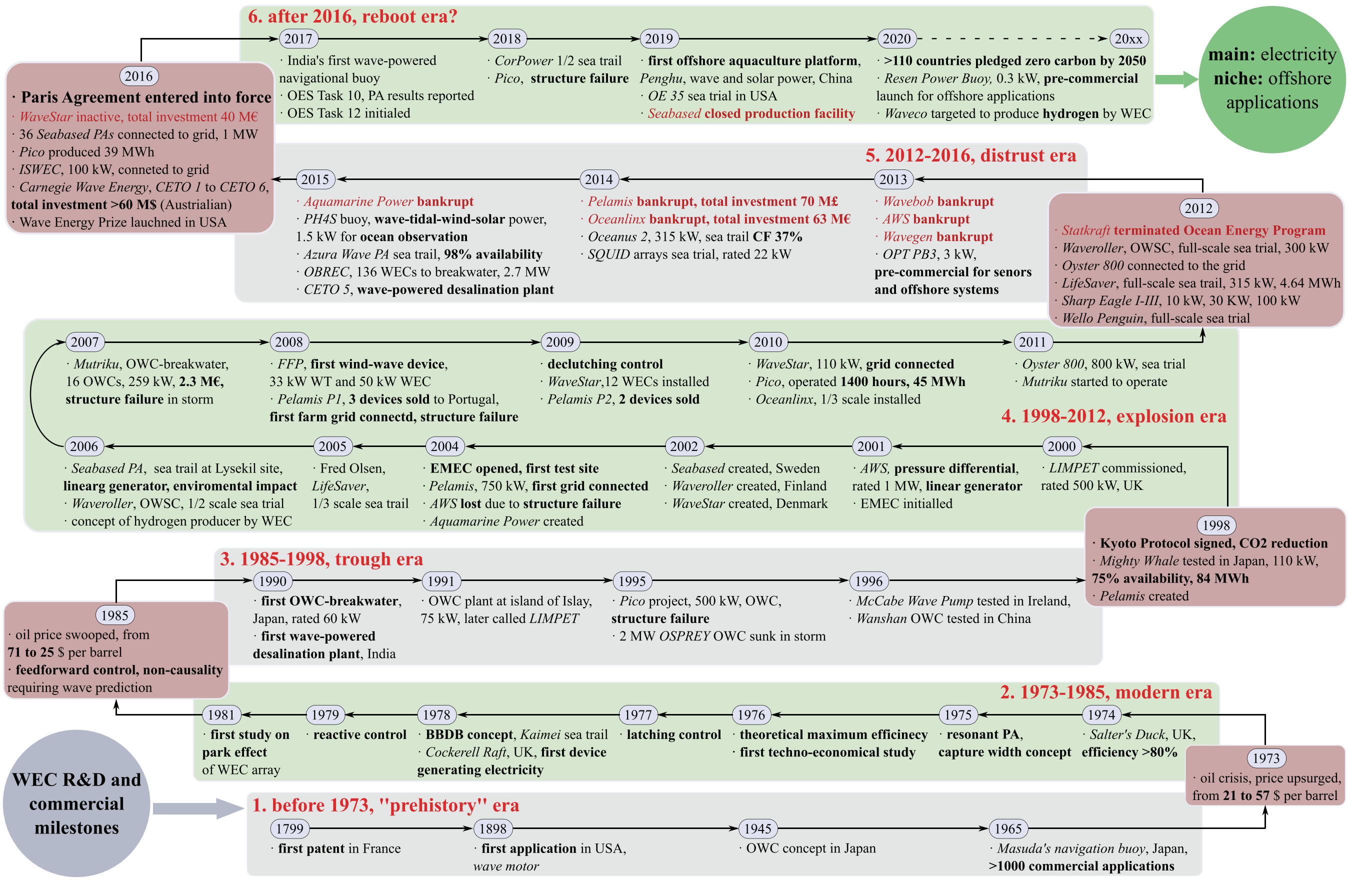

FIGURE 11 Historical development of wave energy technology

establishing logistics chains, providing grid connection and easing legal permitting. With better understanding of WEC technology and its mitigated risk, private investment, that is, seed investment, venture capital and stock investment, may get involved at early stages of WEC technology development. Thus, such a reinforced IAG collaboration shows a possibility to bridge the VoD for commercial success.

6 | HISTORICAL AND COMMERCIAL EFFORT

This section summarises the historical and ongoing development of wave energy technology, to address both academic and commercial milestones.

6.1 | Historical development of wave energy technology

The idea to transfer wave energy into a useful form is not new, dating back to 1799. Since then, the historical development of wave energy technology is divided into six eras, shown in Figure 11. A notable overview of WEC history development is summarised in [138]. The years of 1973, 1985, 1998, 2012 and 2016 are treated as turning points for WEC development, also used in Figure 11. R&D and commercial activities in each era are detailed in the following subsections.

6.1.1 | 'Pre-history' Era, before 1973

In this era, R&D and commercial activities are not well documented, and most research work is typified by trial-and-error methods. However, there are still some significant fundamental achievements, including: (i) the first patent published in France in 1799 [210]; (ii) the first practical *wave motor* device in the United States, operating from 1898 to 1910 [138]; (iii) the OWC-based navigation buoy developed in Japan from 1945 to 1965, is successfully commercialised with more than 1000 devices deployed worldwide [138]. To the best of the authors' knowledge, the OWC-based navigation buoy is the only successfully commercial WEC device to date.

6.1.2 | Modern Era, 1973–1985

With oil price rising sharply from 21 to 57 $ per barrel in 1973, several countries invest heavily in renewable energy technologies. The landmark of WEC technology entering into the

TABLE 4 Some typical pre-commercial wave energy converters

WEC	Country	Developer	Type	Stage	Capacity (kW)	Year	Status	Reference
KAIMEI	Japan	JAMSTEC	OWC	4	40	1978-1979	decommissioned	[35, 222]
TAPCHAN	Norway	Norway A.S.	TWEC	4	385	1985-1989	destroyed by storm	[218, 223]
Kvaerner OWC	Norway	Kvaerner Brug A/S.	OWC	4	500	1985-1989	destroyed by storm	[138, 219]
Islay OWC	UK	QUB, Wavegen	OWC	4	75	1991-2000	replaced by *LIMPET*	[224]
OSPREY	UK	Wavegen	OWC	4	2000	1995	lost during installation	[32, 138]
Mighty Whale	Japan	JAMSTEC	OWC	5	110	1998-2000	decommissioned	[225, 226]
Pico OWC	Portugal	IST, WavEC	OWC	4	400	1999; 20016-2018	turbine fault;	
damaged by storm	[220]							
LIMPET	UK	QUB, Wavegen	OWC	4	500	2000-2012	stopped	[224, 227]
AWS	Netherlands	Teamwork Technology	PA	4	1000	2001;2002; 2004	lost due to	
pump failure	[228, 229]							
Pelamis	UK	Pelamis Wave Power	AWEC	5	750	2004-2007; 2010-2011	structure failure 2011	[230]
SeaBased	Sweden	Seabased Industry	PA	5	10 × 10	2005-2007	decommissioned	[231, 232]
WaveRoller	Finland	AW-Energy OY	OWSC	4	350	2007-2008	decommissioned	[233]
PowerBuoy	United States	OPT	PA	4	40	2009-2010	decommissioned	[234]
Mutriku	Spain	EVE	OWC	5	296	2009-	active	[235, 236]
Oyster 800	UK	Aquamarine Power	OWSC	4	800	2012-2015	stopped	[237]
BOLT LIfeSaver	Norway	Fred. Olsen	PA	4	30	2015-2016	stopped	[238, 239]
greenWAVE	Australia	Oceanlinx	OWC	4	1000	2014	damaged during transportation	[240]
Eagle Wanshan	China	GIEC	AWEC	4	100	2015-2016	stopped	[241]

modern era, is the proposal of *Salter's Duck*, whose hydrodynamic efficiency is tested up to 80% [211]. In this era, theoretic fundamentals are established, including: (i) the concepts of 'resonance', 'absorption length' and 'power optimisation' are defined for the first time in [168]; (ii) the theoretical maxima of absorption are derived in [212]; (iii) latching control [213] and reactive control [214] are tested; (iv) the constructive park effect of WEC arrays is studied for the first time in [215]; and (v) the first economic study of WEC technology is given in [216]. In addition, there is also some practical progress, represented by the sea trial of the *KAIMEI OWC* and *Cockerell Raft* concepts.

6.1.3 | Trough Era, 1985–1998

In 1985, the oil price drops from 71 to 25 $ per barrel, and activity in renewable energy decreases dramatically. However, there are still some noteworthy milestones. In theory, feedforward control is studied to overcome the non-causality [217], while several devices are tested in the open ocean, including the *TAPCHAN* [218], *Kvaerner column* [219], *OSPREY OWC* [32], *Islay OWC* [32] and *Pico OWC* [220].

6.1.4 | Explosion Era, 1998–2012

The Kyoto Protocol is signed in 1998 and carbon emission reduction becomes an international imperative, marking 1998 as the start of the explosion era of WEC technology. A significant milestone is the development of the *Pelamis* device, considered as the most promising WEC technology for commercial application. In this era, pre-commercial activities are stimulated by regional and national support programmes and market incentives, characterised by: (i) WEC companies developing some well-known pre-commercial devices, further detailed in Table 4; (ii) WEC technology evolves from onshore to offshore, from small to large capacity; (iii) a number of open sea testing sites are commissioned with grid connections, with EMEC opening in 2004 as probably the first and most developed test site; and (iv) a number of structure failures are reported, with high financial loss, or total device loss, leading to adverse publicity.

6.1.5 | Distrust Era, 2012–2016

In 2012, *Statkraft* terminated its ocean energy programme, tipping the first domino and opening the distrust era. Several companies, even some highly rated ones, fail to pass through the VoD and go into bankrupcy or liquidation, for example, *Wavebob Ltd.*, *AWS*, *Wavegen*, *Pelamis Wave Power*, *Oceanlinx*, and *Aquamarine Power*. This bad news reduces public and private investor trust, given that the total investment in these companies was significant, for example, about 64 M€ for *Oceanlinx*, and about 81 M€ for *Pelamis*. One positive trend in this era is that some companies turned to niche markets, for example, the *OPT PB3* and *PH4S* buoys for powering ocean observation devices.

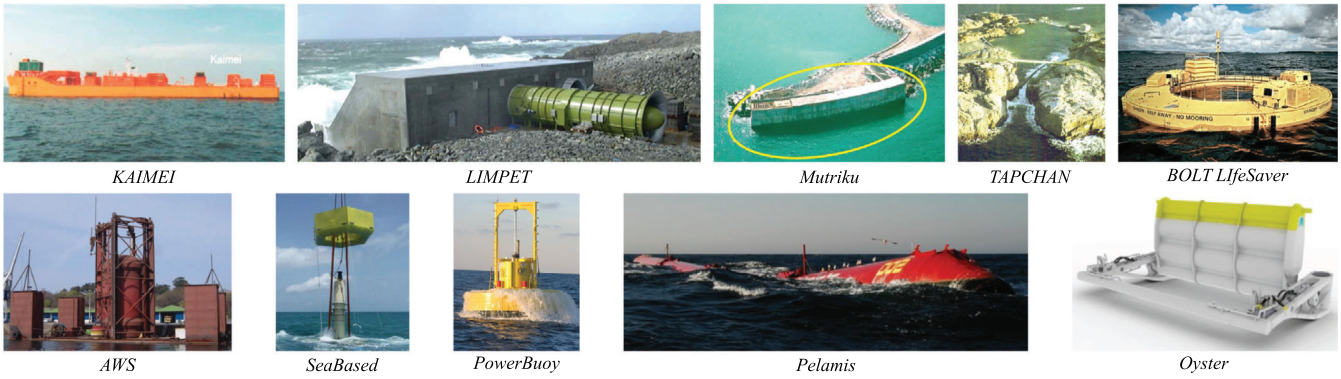

FIGURE 12 Photos of some pre-commercial WEC devices in Table 4, including the *KAIMEI* [36], *LIMPET* [36], *Mutriku* [36], *TAPCHAN* [242], *BOLT LIfeSaver* [242], *AWS* [242], *SeaBased* [243], *PowerBuoy* [244], *Pelamis* [230], and *Oyster* [242] devices

6.1.6 | Reboot Era, 2016–present

In 2016, the Paris Agreement entered into force, producing consequent activity increases in regional and national support schemes. Meanwhile, *WaveStar* becomes inactive after 13 years of operation, following 40 M€ of investment. Then, *Carnegie Clean Energy* receives more than 39 M€ total investment, and wave energy was successfully applied to an aquaculture platform. However, *Seabased* closes its production facility in Sweden and the *Pico* plant suffers from structural damage in a storm. Following the Paris Agreement, more than 110 countries pledge to reach zero carbon emission by 2050, suggesting a boom in public and private renewable energy investment. Even though wave energy is more challenging to harvest than other renewable energy resources, WEC technology is well poised to be rebooted by increased national support strategies and market incentives, and reinforced IAG collaboration.

6.2 | Pre-commercial development of wave energy

As mentioned in Section 6.1, the OWC navigation buoy developed in Japan is the only successful commercialisation case, with no full-scale commercial WEC farm in operation. *Commercial devices* refer to WECs that are: (i) characterised by high TRL and TPLs, that is, (TRL,TPL)=(9,>7); (ii) fully functioning, with affordable electricity for utility markets or reliable power supply for niche markets; and (iii) market accessible with specific product availability. Current WECs cannot fully satisfy (ii) and (iii), though some can meet (i), referred as pre-commercial devices.

This subsection only summarises pre-commercial WEC projects and related R&D activities, with some well-known pre-commercial WECs listed in Table 4 and Figure 12. In Table 4, the development stage is defined according to the TRL [66], as shown in Table 3. It can been seen that only the *Mighty Whale*, *Pelamis*, *Mutriku* and *SeaBased* devices are at stage 5. Most pre-commercial devices are based on OWC or PA concepts, showing high consistency to the R&D foci reviewed in [11, 62, 221].

6.3 | Prospects for commercialisation

Learning from the operational experience of pre-commercial WECs in Table 4, some recommendations for commercialisation may be made: (i) System survivability should be the most important concern for commercialisation, as several WECs suffered from structure failure in storms. (ii) The WECs in Table 4 require significant development funding and time, mostly developed along the TRL-first trajectory. Without considering TPL at early stage of WEC development, WEC projects may fail purely due to poor installability or transportability, for example, the *OSPREY* and *greenWAVE* devices. Thus, the TPL-first development trajectory is strongly recommended to save development cost and time, and to mitigate development risk. (iii) The real performance of various pre-commercial WECs is not as optimistic as expected, potentially due to optimistic power production estimates (from linear models) or capacity factors. The capacity factor in long-term testing is low [220, 236], for example, 0.11 [236], but is over-optimistically estimated as 0.3 in LCoE assessments [59, 245]. Efforts to reduce the uncertainty in LCoE assessment are important in improving investment decisions and investor confidence.

7 | MARKET OPPORTUNITY FOR WAVE ENERGY

The dominant target market for wave energy technology is utility-scale electricity, though R&D and commercialisation activities towards niche markets are also emerging. Both of these market opportunities are now separately considered.

7.1 | Utility market

As mentioned in Section 1, there exists a conflict between the increasing global energy demand and carbon reduction promises [3], with a focus on renewable energy technologies to provide carbon-free electricity. However, the current LCoE of wave energy is estimated at a high level, ranging 120–470

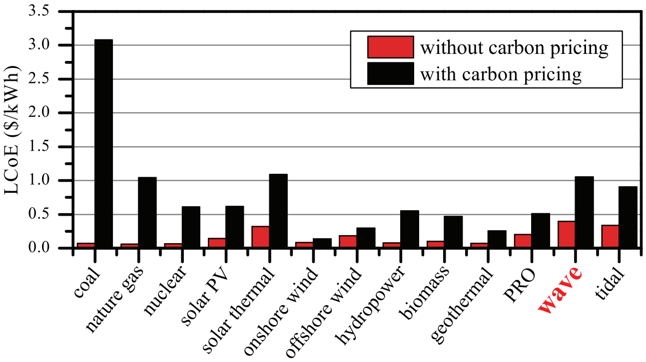

FIGURE 13 LCoEs of different technologies in the United States, with or without carbon pricing, in black and red, respectively, data from [246]

$/MWh (about 100–400€/MWh) [59]. Compared with other mature renewable energy resources, for example, solar and wind power, or fossil fuels, wave power is not competitive or market viable in the utility market [246], as shown in Figure 13. If carbon pricing is applied to the energy technologies in Figure 13, renewable energy resources will have lower an LCoE than fossil-based resources. In this scenario, wave energy technology is, indeed, marketable.

As wave energy technology is untapped, its LCoE can be further reduced to 100–300 $/MWh (about 84–252 €/MWh) for GWs of installed capacity, and to 100–150 $/MWh (about 84–126 €/MWh) for 10 GW installed capacity [59]. With accumulated operation experience, a recent OES annual report projected that the LCOE of wave energy can be reduced to 100–150€/MWh by 2030–2035 [247]. Thus, electricity from wave energy is expected to be competitive in the utility market.

In addition, wave energy can be treated as a complementary source for offshore wind farms [14, 17], and the combination of wind and wave energy results in legislative and technical synergies for both technologies [15], to reduce the LCoE further. However, such a combination strongly depends on installation sites [18], and an ideal site, characterised by less extremes, elevated mean values, stable behaviour and low correlation, will result in a more smooth output and fewer hours of zero production. The Irish coast is such an ideal site for wind-wave integration [14, 17], where wind and wave resources are low correlated, and joint wind-wave farms can mitigate against the high-frequency variability in both resources.

WEC technology, with accumulated install capacity at GWs, shows a great potential for the utility market by providing carbon-free and affordable electric, but still unattractive to private investors, as its R&D and commercialisation activities are still costly and risky to invest in.

7.2 | Niche market

As mentioned in Section 6.1, the only successful commercialisation of WEC technology is the OWC navigation buoy, which belongs to a niche market rather than the utility market. For the past decade, many countries have established regional or national strategies to develop their 'blue economy'. Thus, ocean-based applications, for example, ocean observation and desalination, and fish farming, are growing, and require an economical and clean power supply [248]. Wave energy can meet such energy demands to advance the blue economy, where alternative (especially conventional) energy sources can be prohibitively expensive, due to the relatively remote consumption point.

Ocean-related niche markets include: (i) ocean navigation and observation [249], (ii) coastal protection [250–252], (iii) desalination [253, 254], (iv) island micro-grid [138], and (v) marine aquaculture, (vi) multi-function offshore platforms [255, 256], and (vii) other applications, for example, underwater vehicle charging, disaster recovery and resiliency, seawater mining and marine algae [248]. These potential niche markets are well summarised in [22, 221, 257].

Compared with the utility market, the rated capacity for niche markets is much smaller, ranging from several Watts to hundreds of kW. Such a relatively small capacity may result in a small geometric dimension, consequently reducing development time, cost and risk, which make it more appealing to public and private investment, with potential investors already coming from financially secure application domains, showing strong potential to pass through the VoD to a commercial success. It is also expected that rapid growth in wave energy niche market applications can assist the development effort for the utility market, by accumulating operation and maintenance experience, as well as WEC system design expertise.

7.3 | Prospects for commercialisation

To sum up, the potential size of the utility market is up to TWs, but current wave energy technology has not fully demonstrated its competitiveness with respect to other energy technologies. As technical, economical and administrative challenges coexist, reinforced IAG collaboration is strongly recommended to advance the TPL of wave farms for the utility market. Niche markets in ocean applications have been emerging, and wave energy shows promising potential in providing clean and economic power supply for ocean-based applications. However, the market size is still unknown, and only limited operational experience is available, creating cost uncertainties. Longer term operations are required to further quantify the commercial potential of wave energy technology for niche markets.

8 | FACTORS AFFECTING THE DEVELOPMENT OF WAVE ENERGY

Recalling the historical development of wave energy technology, as documented in Figure 11, key factors that significantly influence the development of wave energy technology can be separated into external factors, for example, fossil fuel price, development of other renewable energy technologies, and national/community factors, for example, supporting strategies and market incentives, which are discussed in the following two subsections.

TABLE 5 National schemes for ocean energy, data from [260]

	National strategy				Market incentive				
Country	**Capacity Target**	**National Action Plan**	**Technology Roadmap**	**Marine Spatial Plan**	**Feed-in Tariff**	**Contract for Difference**	**Green Certificate**	**Quota obligation**	**Renewable Energy Auction**
Belgium			•	•			•		
Canada	•	•	•	•	•				
China	•	•		•			•		
Denmark			•						
France	•			UD	•				
Germany				•	•				
Ireland	•	•	•	UD	•				
Italy	•				•				
Japan		•	•		•				
Korea	•	•	•					•	
Mexico	•		•				•		
Netherlands				•	•				
Monaco				•					
Norway				•			•		
New Zealand				•					
Portugal	•	•	•	•					
South Africa				•					
Spain	•								•
Sweden		•		UD			•		
UK	•	•	•	•		•			
United States		•		•					

8.1 | External factors

In Figure 11, 1973 and 1985 can be clearly identified as turning points, mainly due to the rapid changes in oil price in those years. Oil prices surged from 21 to 57 $ per barrel in 1973, resulting in a corresponding surge in wave energy development, while the price collapsed from 71 to 25 $ per barrel in 1985 consequently disincentivised R&D development. Although fossil fuel prices comprise one of the most important factors, such a causal factor is somewhat unpredictable, though (despite new recovery methods such as fracking) one can only imagine that fossil fuels will become increasingly more expensive, with dwindling supply.

In Figure 11, 2012 is also marked as a tipping point, in which a series of WEC company failures were indicative of the currently low marketability of WEC technology in the utility market. Compared with other renewable energy technologies, for example, wind and solar power, current WEC technology is untapped and uncompetitive with a high LCoE, as shown in Figure 13. One hard lesson learnt from some failed projects is that the TPL-first development trajectory should be used, to address technology performance at early development stages. With costs scaling up exponentially with scale, a premature rush to high TRL levels has been shown to be costly. The repercussions of some high profile WEC company failures are still felt in the wave energy community. Perhaps, over-optimistically, wave energy technology is projected to achieve a competitive LCoE at 100-150 €/MWh by 2030–2035 [247].

A further external factor is the rapid rise in other renewable energy technologies, for example, in offshore wind (including floating offshore wind) [258, 259], which builds on many years of expertise experience in wind energy, with incremental technical problems only to be solved, while wave energy still wrestles with fundamental issues. The rapid acceleration in offshore wind has garnered both offshore technologists and investors from the wave energy sector.

8.2 | National strategies and market incentive

For public investors, for example, governments, the benefits of investing in wave energy are many, including (i) environmental benefit, achieving carbon neutrality; (ii) broadening of the energy mix and provision of greater energy security; and (iii) economic benefit, for example, industry and job creation,

TABLE 6 Feed-in tariff in some countries, data from [260, 264 268, 269]

Country	Strategy	Capacity (MW)	rate (€/MWh)	duration (Year)
Canada	Ontario FIT	<5.5	170	40
China	FIT	–	330	–
France	FIT	–	173	–
Germany	FIT	<50; >50	124; 34.7	–
Ireland	FIT	–	260	–
Italy	FIT	< 5; >5	300; 190	15
20				
Netherlands	Subsidy	–	130	–
Philippines	FIT	–	310	–
UK	CfD	–	360	–

blue economy. Based on the OES annual report in 2017, some national supporting schemes for ocean energy are detailed in Table 5, within which UD means under development.

In Table 5, national strategies include: (i) capacity targets, to express national commitment to ocean energy deployment; (ii) action plans agreed by public and private sectors to facilitate deployment; (iii) roadmaps, providing long-term frameworks for developing policies and supporting actions; and (iv) marine spatial plans, to remove administrative barriers. As ocean energy resources and market data vary from country to country, national strategies developed by each country also vary and are detailed in [260]. Roadmaps with specified long-term pathways are important to mobilise national efforts to improve ocean technology, which are articulated in a number of countries, for example, UK [261], Denmark [262], and Ireland [263]. Additionally, national policies for innovation, manufacturing and deployment of ocean energy are discussed in [264].

Table 5 also summarises several commonly applied market incentives, of which the FIT is the most common supporting measure, as it can directly improve the profitability of ocean energy projects. Since 2014, the UK has provided the 'contract for difference (CfD)' mechanism to replace its original used FIT scheme [260]. The FIT and CfD schemes belong to market-pull incentive, while the others fall into the market-push class [265]. FIT is one of the most successful incentive schemes for promoting the growth in wind and solar power [266], and is naturally expected to have significant influence on encouraging private investment in wave energy. For wave energy technology, sensitivity of net present value to FIT variation is analysed in [63, 267], which also address the effectiveness of FIT schemes, in relation to its impact sensitivity on project profitability [63]. This reveals some of the rationale for policy makers to applying FIT schemes to encourage private investment. Some active FIT supporting schemes are summarised in Table 6, which can prolong public investment and encourage corresponding private investment to bridge the VoD.

Occasionally, governments invest directly in interventions and mechanisms that accelerate the development of wave energy intellectual property (IP), in addition to providing FIT support schemes. Such interventions are somewhat altruistic, since the benefits of directly supporting fundamental technology development can be potentially enjoyed by many other jurisdictions. However, maintaining and supporting wave energy IP development directly brings the capability to generate a significant export industry and supply chain, which is of potentially greater long-term value than the development of wave farms locally. Although many jurisdictions provide general funding schemes for both R&D and commercialisation, Wave Energy Scotland is somewhat unique in dedicating funding to wave energy IP development, originally founded to retain and manage the IP held by Scottish companies *Pelamis Wave Power* and *Aquamarine Power*, following their demise in 2014 and 2015, respectively. In a more measured way, some jurisdictions have included ocean energy as one of the national research priorities, for example by Science Foundation Ireland in 2013, giving some level of preferential treatment to research and R&D proposals in this area.

9 | CONCLUSIONS

This review summaries the historical and ongoing research and commercialisation efforts devoted to wave energy technology. Significant spatial and temporal variability in the wave power resource has a fundamental role in diversifying the development of successful WEC concepts, with a need for a collective approach to common fundamental issues, such as modelling, PTO and control design, survivability, and performance metrics. Regarding technology development trajectories, TPL must clearly be prioritised over TRL, particularly at early project stages. Clearly, investor risk must be reduced by providing more certainty in national and international support programmes, focussing on common technological challenges, to reduce LCoE, LCoE uncertainty and to examine limitations in supply chains and marine licensing arrangements, and maximisation of the potential of IAG collaboration.

Historical analysis has shown that survivability and installability are key metrics, which not only affect the economics and success of individual wave energy projects, but also play a large role in sector confidence and investability. With increasing emphasis on the provision of carbon-free energy, and a need to diversify the mix of renewable energy sources, wave energy is well poised to supplement, and complement, existing and more mature renewable energy technologies. The next decade will be crucial in deciding if wave energy can make the breakthrough needed to become a mainstream renewable energy technology.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable as no new data generated, or the article describes entirely theoretical research.

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