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REVIEW

Grid integration aspects of wave energy—Overview and perspectives

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Abstract
The sustained development of wave energy in the past two decades makes it one of the most promising renewable energy resources to be added to the diverse mixture of supply systems. The inherent difficulty of grid integration of wave energy involves various aspects such as suitable control of power converters and power conditioning processes, allowing for the extraction of the best quality power. This paper presents a comprehensive review of different aspects of grid integration of wave energy devices, including classification of wave energy devices based on their impacts on grid integration, grid requirements imposed by the grid codes and storage technologies used for the grid integration of wave energy converters (WECs). This study also analyses various grid integration studies on wave energy converters, with particular emphasis on power converter technology and control. Furthermore, specific attention is given to the combinational studies that use wave energy combined with other renewable resources due to their positive synergies in lowering the costs of energy produced and that hold an opportunity for future research. An economic case is presented for wave energy devices based on value on the grid.

1 | INTRODUCTION

Renewable energy technologies such as solar and wind energy has been significantly improved in the recent past, and now hold a significant share of total renewable energy generation. Wave energy, on the other hand, has not been developed as much as solar and wind, despite being one of the oldest technologies available [1, 2]. The trend is changing now, and many researchers and scientists are focusing on wave energy as it is one of the most abundantly available clean energy resources. Their research has led to the development of various wave energy devices which are currently being implemented across the globe [3].

Wave energy will be an enabler of the transition towards 100% renewable energy generation for the following reasons:

1. The temporal predictability of wave energy is better than wind energy, leading to a better day-ahead forecasts and reduced balancing costs [4].
2. Adding wave energy to the currently available mix of renewable energy sources will increase the reliability of the supply systems as wave energy has more consistent production profiles than that of solar and wind [1, 2, 5]. This will enable the supply system to be more accepting of renewable energy at lower costs as compared to the existing system, which heavily relies on only wind and solar energy.
3. Although Levelised Cost of Energy (LCoE) for wave energy devices is higher than that of wind and solar, its Levelised Value of Energy (LVoE) is lower. The LVoE explains the correlation between power market prices and renewable energy resources. Wave power has a positive correlation to power market prices as compared to both wind and solar, which has a negative correlation [6].

The wave energy conversion system consists of four stages, namely absorption, transmission, generation and conditioning, as shown in Figure 1 [7]. Each stage of the conversion system has its dynamics and constraints. Many studies focus only

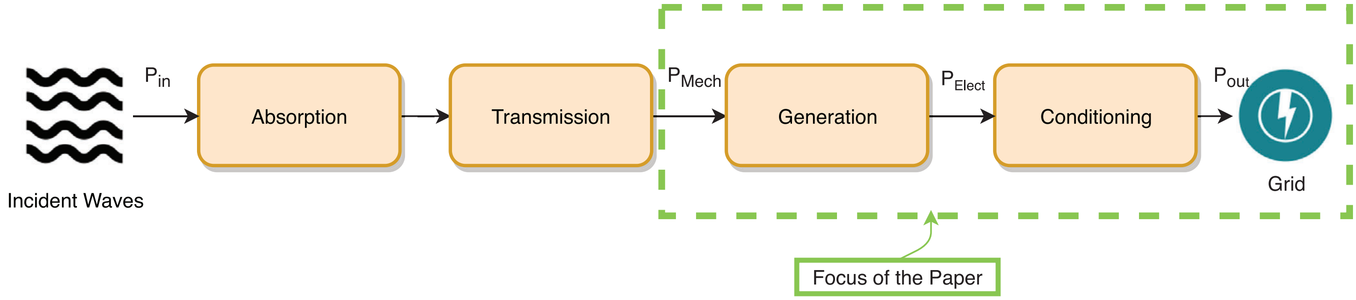


FIGURE 1 A typical wave energy conversion system

on one specific stage of the conversion process and ignore the interaction among the different stages, for example, in [8], the authors describe the converter models (conditioning stage) in detail for this grid integration study but ignore the complexities of the hydrodynamic model. Rather, it is necessary to take all stages into account and make a balanced fidelity model for grid integration studies. The process of making a model which contains all the subsystems and their interactions is referred to as wave-to-wire (w2w) in the literature [7, 9, 10]. In [7], the four stages of a w2w model, the dynamics involved and the constraints of each component are explained in detail, keeping the focus on assembling a w2w model for control studies. In [10], the main focus is to review control strategies and their validation for w2w models.

The power output of wave energy devices is not ideal, due to the variability of the wave resource, and it cannot be directly connected to the grid in a traditional manner. Grid integration process encompasses various problems ranging from suitable control of power converters involved and power conditioning processes. Some grid integration experiences from wind can be ported to the wave energy case [11, 12]. However, the penetration of wave energy into existing grid networks will directly depend upon the negative effects it will have on the grid and the availability of technology to tackle these effects [13].

The objective of this study is to present a comprehensive review of all aspects of grid integration of wave energy. These aspects include Wave Energy Converter (WEC) classification concerning their characteristics as seen from a grid integration perspective, grid requirements imposed by the grid codes and a review of grid integration studies with an emphasis on control, power converters, storage and impact on the grid. Also, we investigate the interaction of wave energy with other renewable energy resources. It should be noted that the economics of wave energy are also studied and an economic case for value of wave energy is presented.

The remainder of the paper is organised as follows: Section 2 describes a classification of the WECs based on their inertial characteristics, while Section 3 discusses grid requirements imposed by transmission system operators (TSOs). A comprehensive review of grid integration studies of WECs is presented in Section 4, with Section 5 discussing the prospects of combining wave energy with other renewable energy resources to gain synergistic advantages. Section 6 presents an economic perspective on the grid integration of wave energy, while Section 7 concludes this study.

2 | TYPES OF WAVE ENERGY CONVERTERS

Various wave energy devices have distinct characteristics with respect to grid connection, due to their different power output profiles which, in turn depends on inertial characteristics of each device. The inertial characteristics of a generating plant can be defined as that property of the generator mass which overcomes an immediate imbalance between supply and demand. The classification of WECs can be based on working principles, or on a location basis, as shown in Figure 2. For grid integration studies, it is essential to classify WECs on the basis of their inertial characteristics.

The selection of a WEC for potential deployment is usually based on its power matrix characteristics, which estimate the mean annual power absorbed by a WEC. The sea state, in a power matrix, is generally characterised by two parameters: (i) significant wave height and (ii) peak wave period. However, the use of the power matrix is prone to errors due to model inaccuracies and oversimplification of the wave spectrum. Mérigaud and Ringwood [14] detailed these errors and proposed a computationally efficient method to achieve accurate average power estimates. Additionally, variability of WEC power production over various scales (time and geographical) is a concern for assessment studies. In a benchmark study, for the selection of WECs [15] performance measures were deduced, including absorbed energy per characteristic mass, per characteristic surface area, and per Root Mean Square (RMS) value of Power Take-Off (PTO) force.

For grid integration studies, in particular, a device with a more constant power output will be easier to connect to the grid, since less power conditioning is needed. In short, a WEC device with the spectral characteristics of a low pass filter is a good choice for grid integration. Furthermore, if we analyse the power train of a typical wave energy conversion system, as shown in Figure 1, all parts of the train should work in harmony before connecting to the grid [16]. In the case of wave energy devices, maximising absorbed hydrodynamic power and generator speed

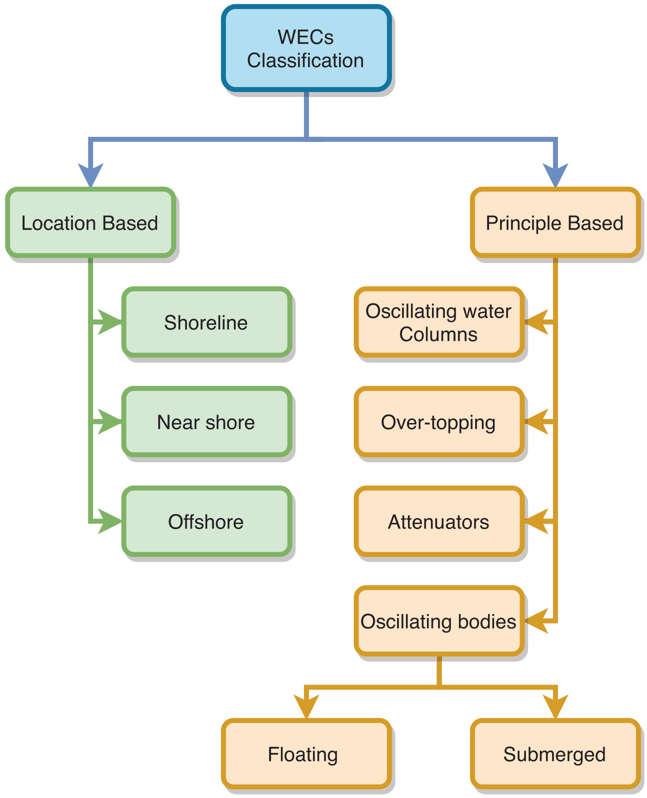


FIGURE 2 Classification of WECs

objectives do not always align. Therefore, variable speed generators are used. Energy maximising controllers increase the efficiency of devices by varying the speed; hence the Squirrel Cage Induction Generators (SCIG) are at a disadvantage due to their minimal speed variability. The use of Induction Generators (IG) and Doubly-Fed Induction Generators (DFIG) is also discouraged for wave energy application, despite their higher efficiency and lower cost, due to difficulties in maintenance for offshore devices [17].

However, the inertial characteristics of WECs are also dependent on the PTO each device uses. Some PTOs are very device-specific, such as Oscillating Water Column (OWC) turbine/generator, and overtopping devices with reservoir/hydro turbines. In contrast, other PTOs are more generic and can be used with multiple devices such as hydraulic PTOs and direct drive PTOs. In this regard, a new classification can be described as follows: [18, 19]

1. Devices with specific PTOs:
    a) OWC with turbine/generator
    b) Overtopping with reservoir/hydro turbine
2. Devices with generic PTOs:
    a) Point absorbers
    b) Wave surge converters
    c) Attenuators
    d) Other devices

2.1 | Devices with specific PTOs

2.1.1 | OWC with turbine/generator

OWC devices produce energy from waves using air in a hollow chamber which is compressed and decompressed via wave action (see Figure 3(a)). A ducting mechanism is employed in the device to increase the velocity of the airflow, and this high-speed airflow turns an air turbine (Wells/impulse) [21]. Wells turbines can drive low pole (2–4 poles) high-speed generators while impulse turbines are relatively slow and use 6–8 pole generators [19]. Due to the inherent variability of the airflow, a wide operating speed range is required, and the device is optimised in such a way that it extracts maximum efficiency over a specific duration. The mechanical system (turbine and generator) provides the inertial response for this device, since it does not have any inherent storage. Examples of such devices are LIMPET, OE buoy and Mutriku WECs [22–24].

2.1.2 | Overtopping devices with reservoir/hydro turbine

The working principle of the overtopping device is very similar to a hydroelectric dam. Incident waves flow onto the ramp, and the water is captured in a reservoir which is then used to drive a low head turbine as shown in Figure 3(b). Key advantages of using the overtopping device include unidirectional power flux, and the presence of a large reservoir which allows this device to use a constant speed turbine which drives the generator. The presence of the reservoir also smooths the resource variability effects on the generator and improves inertial characteristics. The nominal speed of conventional hydro turbines is of the order of 100–300 rpm, which is quite low and requires a carefully designed gearing mechanism while using with overtopping devices [19]. Wave Dragon is an example of an overtopping device [25].

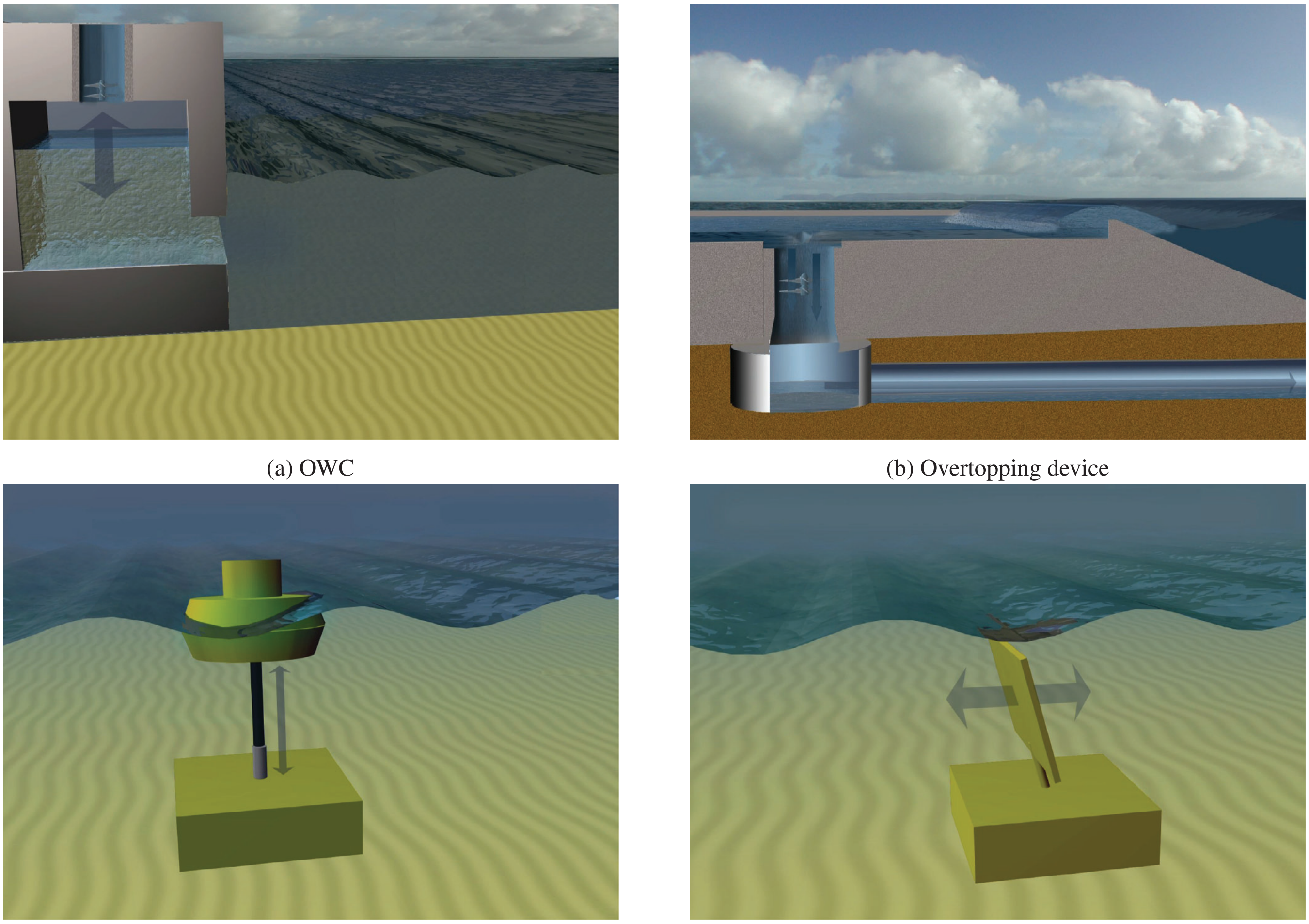
2.2 | Devices with generic PTOs

2.2.1 | Point absorbers

Point absorbers generally have two parts, where the relative motion between these parts, due to incident waves, results in energy production as shown in Figure 3(c). The upper floating part moves while the lower part can either be moving or fixed. Point absorbers can be floating or submerged. Examples of such WECs are the CorPower WEC [26] and Archimedes Wave Swing (AWS) [27].

2.2.2 | Wave surge converters

Wave surge converters are oscillating devices placed on the sea bed in shallow waters. The "flap" of the surge converter moves



(a) OWC (b) Overtopping device

(c) Point absorber (d) Oscilating wave surge converter

FIGURE 3 Types of WECs [20]

to-and-fro in the manner of an inverted pendulum attached to a pivot as depicted in Figure 3(d). Oyster by Aquamarine is an example of a wave surge converter [28].

2.2.3 | Attenuators

Attenuators are floating devices, placed on the sea surface ideally parallel to the direction of incident waves. Energy is produced by the relative motion of two arms of the device. The Pelamis WEC is an example of an attenuator device [29], with a more recent evolution being the MOcean device [30].

2.2.4 | Other devices

Less established wave energy devices [31], such as rotating mass, wave rotor, and bulge wave, are considered here. Rotating mass devices use a heavy mass displaced by the incident waves, and a rotating generator converts the mechanical energy of the mass into electrical energy. An example of a rotating mass WEC is the Wello Penguin [32]. Such a device's inertial characteristics are improved by the oscillating mass of the device, which actively contributes to the power generating unit's inertia. Wave rotor devices, such as WEPTOS WEC [33], consist of multiple rotors that pivot around a common axle to absorb wave energy. The absorbed energy is transferred through the axle to a common PTO mechanism [34]. In contrast, a bulge wave energy converter, such as the Anaconda [35], uses an entirely different principle to produce energy. It uses a flexible pipe to collect water on one end, with wave motion forcing the progression of water along the pipe to create a bulge wave. The bulge wave then drives a turbine/generator set at the other end of the tube to produce electrical energy [36].

2.3 | Generic PTOs

The power take-off mechanisms that can be used with a variety of devices are categorised as generic PTOs. Before going into the description of the individual type, it is essential to note that a PTO or power transmission stage consists of two main parts: a rectifying unit which converts the (normally) reciprocating motion of waves into unidirectional motion, and a conditioning unit which may or may not have temporary storage plus a prime mover which essentially drives the generator. The main types of these PTOs are,

1. Hydraulic PTOs
2. Direct drive PTOs

Hydraulic PTOs are a widely used PTO mechanism due to their high controllability, ease of power flow rectification and high force density for low velocities [7]. A typical hydraulic transmission system consists of hydraulic cylinders, rectifying valves, accumulator, hydraulic motors and hydraulic reservoir. The hydraulic cylinder connects the converter with the hydraulic circuit. The reciprocating motion of the device is converted into a unidirectional motion with the help of rectifying valves. The cylinders push the fluid into accumulators which provide short term storage and provide relatively smooth fluid flow to drive the hydraulic motor which may allow for the use of a constant speed generator such as a SCIG [37]. Also, it allows for potential direct grid connection, rather than converter connection [38].

Direct drive PTOs use permanent magnet generators that are linear or rotary. Linear Permanent Magnet Synchronous Generators (LPMSG), as direct drive PTOs, are found to be the best option by Baker [39] after the analysis of linear generator technologies. In the linear case, the WEC is directly connected to the translator of the generator by a mechanical link [40], while in the rotary case the mechanical link is in the form of a pulley, gears, or a clutching mechanism to convert linear motion into rotary motion. Due to the inherent variable speed nature of these kinds of generators, the inertial performance of devices with direct drive PTOs is not very good. This can be improved by adding an external storage component. However, the absence of inertial storage makes it difficult for these devices to connect to the grid and these devices have to absorb high peak torque pulses, which increases the ratings of the power conditioning stage components [19].

3 | GRID REQUIREMENTS AND POTENTIAL CHALLENGES

The electric grid consists of a large number of components such as generating stations (thermal, hydro, solar, wind, and wave etc.), transmission systems (LV, MV and HV), and distribution systems. All of these systems work in harmony to provide uninterrupted power to consumers. Power quality is paramount for the grid connection of any power plant. Wave energy converters produce fluctuating power output due to the oscillations of WEC devices. These power fluctuations are very harmful to the grid if connected without a proper power conditioning mechanism. Power conditioning may involve appropriate control strategies or substantial energy storage. Due to the complex nature of power grids, rules were developed (grid codes) which govern all aspects of grids including planning, design, connection requirements and operational tasks. This paper will focus on the connection requirement elements of the grid codes. Furthermore, due to the increase in renewable energy generation and their intermittent nature, grid codes have also been revised to incorporate changes created by this renewable energy influx. For example, a review of such requirements for wind farms, in various countries, is presented in [41].

Every country has its own grid codes which are specified by the Transmission System Operator (TSO). For example, in Ireland, EirGrid [42], in the UK, National Grid ESO [43] and, in Pakistan, National Transmission and Dispatch Company (NTDC) specify these grid codes [44]. A comparison of grid codes for various countries is presented in [45]. The grid connection requirements, guided by these grid codes, are explained below:

TABLE 1 Voltage variations allowed for Ireland [42] and the UK [43]

Grid connection voltage		Nominal operating ranges	
Ireland	UK	Ireland	UK
110 kV	132 kV	105–120 kV	132 kV ±10%
220 kV	275 kV	210–240 kV	275 kV ±10%
400 kV	400 kV	370–410 kV	400 kV ±5%

3.1 | Voltage variations

Grid codes specify voltage variations for new component to be connected to the grid. Voltage variations are of two types, long term and short term. For long-duration, variations, a percentage or a range of the grid voltage is specified. For example, for grid connection voltage at 400 kV, ±5% of voltage variations are allowed for the UK grid [43] while, in Ireland [42], the range of voltage is from 370 to 410 kV. Various long-duration voltage variations for Ireland and the UK are given in Table 1.

It is evident from Table 1 that higher voltages can have smaller voltage variations. For fault conditions in the transmission systems, the ranges of the nominal operating voltage changes and time constraints are also implemented.

On the other hand, low voltage variations are mostly concerned with the power quality of the generating plant. These variations include short-term sag, swell, and interruption, and are governed by IEEE standard 1159-2009 [46], which was last revised in 2019 [47]. These variations are classified based on the time duration as instantaneous, momentary and temporary. Details of these short-duration RMS allowable voltage variations are presented in Table 2.

Voltage sag is the sudden dip in output voltage which can be caused by various factors including high power rating motor startup, faults, or by a sudden increase in heavy loads. On the other hand, voltage swell refers to a sudden increase in voltage, and can be caused by a load decrease or by switching in a big enough capacitor. In the case of wave energy, the fluctuations

TABLE 2 Short duration RMS voltage variations [47]

Category	Typical duration	Typical voltage magnitude (pu)
Instantaneous		
Sag	0.5 – 30 cycles	0.1–0.9
Swell	0.5–30 cycles	1.1–1.8
Momentary		
Interruption	0.5–30 cycles	< 0.1
Sag	30 cycles - 3 s	0.1–0.9
Swell	30 cycles - 3 s	1.1–1.4
Temporary		
Interruption	3 s - 1 min	< 0.1
Sag	3s - 1 min	0.1–0.9
Swell	3s - 1 min	1.1–1.2

TABLE 3 Frequency variations and time limits for the Irish grid [42]

Sr. No.	Frequency limits (Hz)	Time duration
1.	49.5–50.5	Continuous
2.	47.5–52.0	60 min
3.	47.0–47.5	20 s

TABLE 4 Fault ride-through requirements for the Irish grid [42]

	FRT times (ms)		
Voltage dip	110 kV	220 kV	400 kV
95% (5% retained)	150	150	150
50% (50% retained)	450	450	450

of output power may induce these types of short term voltage variations in relatively weaker networks [18].

In addition, voltage waveform quality is an essential factor which can be distorted by flicker (rapid voltage fluctuations), phase imbalance and harmonics produced by the switching of power electronic converters. Although harmonics and phase imbalance should be kept under certain prescribed limits, in the case of a wave energy conversion system, the most significant quantity is flicker due to highly fluctuating output power. Flicker is estimated by International Electrotechnical Commission (IEC) standard 61400-21. Assessment tools for resource induced flicker were studied by Sharkey et al. [48] where it is concluded that flicker assessment can be completed on various levels using assessment charts. Another simplified method for flicker estimation for wave energy farms was presented by Blavette et al. [49]. In [50, 51], impacts of wave farms on the grid in terms of flicker is discussed, and it is shown that the number of wave energy converters in a wave farm directly influence the level of flicker present in the power output.

3.2 | Frequency variations

Frequency stability is the most crucial parameter of the grid connection for any generating plant, since small variations in a system's frequency could lead to catastrophic effects, not only on consumers and their equipment, but also on overall grid stability. Parallel operation of generators in a grid is enabled by keeping the frequency in an allowable range, set out by the grid codes. In Ireland and the UK, 49.5–50.5 Hz is the range in which the system should operate [42, 43]. The plant should remain operational even under fault conditions subject to a time constraint. A comparison of frequency limits and time duration for the Irish grid is given in Table 3.

Due to the rapid development of wind farms in European electricity markets, most countries adapt grid codes accordingly [52, 53]. The incorporation of wind farms in the grid codes, for various European countries, can help pave the way for the inclusion of wave farms.

3.3 | Fault ride-through capabilities

Another essential aspect to be considered by generating plants for grid connection is its fault ride-through (FRT) capability. Essentially, if a fault occurs on the power system for short periods, the plant should have the capability to adapt to these faulty conditions. A straightforward solution is to disconnect the plant from the grid, but this is not ideal for the grid network since it may start a chain reaction of disconnection which could lead to a failure of the complete power network [52]. This is why grid codes ensure that the plant complies with its FRT requirements and remains connected to the system even under fault conditions. These requirements for the Irish grid network is given in Table 4.

The natural reaction of generating plants is to increase reactive power injection to the grid to balance out voltage dips due to fault conditions, which induces peak currents potentially harmful for the equipment. Hence, for a plant to be able to work correctly under fault conditions, it must have excellent ride-through capabilities. This is usually achieved through

TABLE 5 WEC-grid models used in literature. Note: LPMG means linear permanent magnet generator, RPMSG means rotary permanent magnet synchronous generator

Ref. No.	WEC	PTO	Frequency
[8, 80–90]	AWS	LPMG	12
[63, 76, 91–95]	Point absorber	LPMG	7
[16, 75, 96, 97]	Point absorber	Rotary generators	4
[98–100]	OWC	RPMSG	3
[101]	Wave surge converter	LPMG	1
[102]	Overtopping device	Rotary generator	1

various control techniques, for example, in [54–58] FRT capabilities were improved by various control techniques like PI, sliding mode control, and neural control, for OWC wave energy devices. It is shown that these controllers improve performance characteristics and enable power extraction under faults and disturbances.

3.4 | Active and reactive power responses and control

Active and reactive power responses of a power generating plant are crucial because they provide grid stability at the time of a fault. For this reason, grid codes employ strict conditions on the power response of a generating station, especially for renewable plants [59]. In this regard, frequency stability is provided by the active power control of the generating plant. For example, according to Irish grid codes, wind power plants must provide active power support and should restore its active power output to 90% of the rated value within 1s after the voltage recovery at 0.9 per-unit (pu) [42]. Generating stations are required to inject reactive power into the grid under voltage dips and other faults, and support voltage regulation.

In the case of wind turbines, these regulations are already established in European grid codes [59–61] and it is anticipated that similar restrictions will be implemented on wave energy devices following their penetration in the grid. Bearing in mind the grid requirements, the potential challenges for grid integration of wave energy can be summarised as follows:

- Voltage fluctuations
- Electromagnetic interference
- Power system transients and harmonics
- Voltage stability problems
- Weak grids
- Switching losses
- Synchronisation
- Grid congestion

4 | GRID INTEGRATION STUDIES OF WECs

Power intermittency is the main issue with grid integration of wave energy [48]. Since there is no consensus on the type of wave energy device or PTO mechanisms, the WEC/PTO combinations presented in the literature are diverse, and involve both direct and indirect connections. Regarding grid integration, direct connection presents many challenges, considering the variability of the resource, usually requiring the addition of a storage component [62]. However, for grid integration of any device, the problem of output power fluctuations is common, and a power electronic conversion system is needed. The controlled switching of these power converters make it possible for wave power output to comply with grid codes [63].

In addition to power converters, with the increase in renewable energy penetration in the electric grid, the importance of the energy storage system becomes vital. Energy storage systems not only allow excess power storage but also improve the power quality of the intermittent and unpredictable renewable generators [64], also provides flexibility to the supply systems by bridging the gap between demand and supply.

4.1 | The role of energy storage in grid integration of wave energy

Wave energy systems cannot provide the inertia response of conventional bulk generators and hence cannot overcome such a power and energy mismatch [65]. The inertia emulation can be performed by incorporating energy storage during the grid integration process, to mitigate the effects of variability and intermittency, which is inherent with the wave energy resource. Furthermore, the rise of combined technologies for renewable integration, with diverse characteristics, increases the importance of energy storage systems. Hence, the use of an energy storage component for grid integration of wave energy allows increased utilisation of this intermittent source by mitigating the effects on the power network and also provide ancillary services to future grids [64].

4.1.1 | Energy storage technologies

There are several options for storage devices available, and the proper selection of these devices for this particular application is vital. With regard to grid integration, the energy storage system performs smoothing of output power, short duration fluctuation suppression and helps in frequency and voltage regulation. A comprehensive review of marine renewable energy storage systems is presented in [66] and can be broadly divided into four categories [67].

1. Mechanical
2. Electrical
3. Thermal
4. Chemical

Mechanical energy storage systems generally have higher power ratings due to the size of the storage component. Mechanical storage includes Compressed Air Energy Storage (CAES), pumped hydro storage, and flywheels, as shown in Figure 4. For grid integration studies, a fast response time and high energy density are required; flywheels might be useful for this purpose among mechanical energy storage technologies, taking into consideration the drawback of high self-discharge levels [68].

Electrical storage technologies, on the other hand, are widely used for grid integration of renewable modalities. These technologies include capacitors, super-capacitors and Superconducting Magnetic Energy Storage (SMES). Higher cycle efficiency and peak power deliverability of these devices make them suitable for grid integration and power quality improvement applications, despite their poor self-discharge response [67].

Thermal energy storage systems can be broadly classified as follows: aquifer low-temperature, and high-temperature thermal energy storage. Due to lower efficiency and the early development stage of low-temperature thermal energy storage systems, systems such as cryogenic energy storage systems are not considered to be a good option for grid integration of wave energy despite having high energy density [68]. On the other hand, high-temperature systems such as sensible and latent heat storage are in use, but lower efficiency makes it difficult for use in grid integration technologies [69].

Chemical energy storage systems are the most widely used storage systems in various industries, including mobile phones, electric vehicles etc., and are classified into conventional batteries and advanced batteries [67]. Conventional batteries are those batteries which are mature technologies such as lead-acid, Ni-Cd and Ni-MH batteries, and are used in a wide range of applications. Advanced batteries include lithium-ion (Li-ion), sodium-sulphur (Na-S) and sodium nickel chloride (NaNiCl) batteries. Li-ion is the most commonly used technology, which can be found in almost every portable electronic device that uses batteries [64]. In addition to the above technologies, electrochemical energy storage systems can also be categorised under chemical storage. These include fuel cells, which come in various forms and are used in many applications, including grid integration, due to their fast response characteristics, the flexibility of power. As a result, they are widely used in grid integration of renewable energy, voltage control and frequency regulation [64, 70].

4.1.2 | Hybrid energy storage systems (HESS)

Combining the characteristics of two or more energy storage devices, and making a combined storage system, constitutes a HESS. HESS is configured for specific applications such as electric vehicles and grid support. For grid integration of renewable energy generation, the use of HESS is becoming popular [71, 72]. HESS usually combines one high peak power device and one high energy device, for example, battery and super-capacitor HESS, or fuel cell and super-capacitor HESS. Both configurations use batteries and fuel cells as high energy devices, and super-capacitors as the high peak power devices. The quick response of super-capacitors and the high energy density of batteries makes such a combination very useful for grid integration studies. In grid integration, high peak power is required to meet sudden load peaks and high energy density is required to store energy in bulk. Generally, these are combined using the following three topologies [73].

Passive topology: In this topology, both sources are connected in series or parallel without any power converter to control the flow of power. This is the simplest topology, but there is no control over the power distribution between the surces.

Semi-active topology: One of the devices is connected through a power converter while the other one is connected directly. This topology allows some level of control over power distribution among the sources.

Active topology: A fully active topology uses power converters for both storage components of HESS and

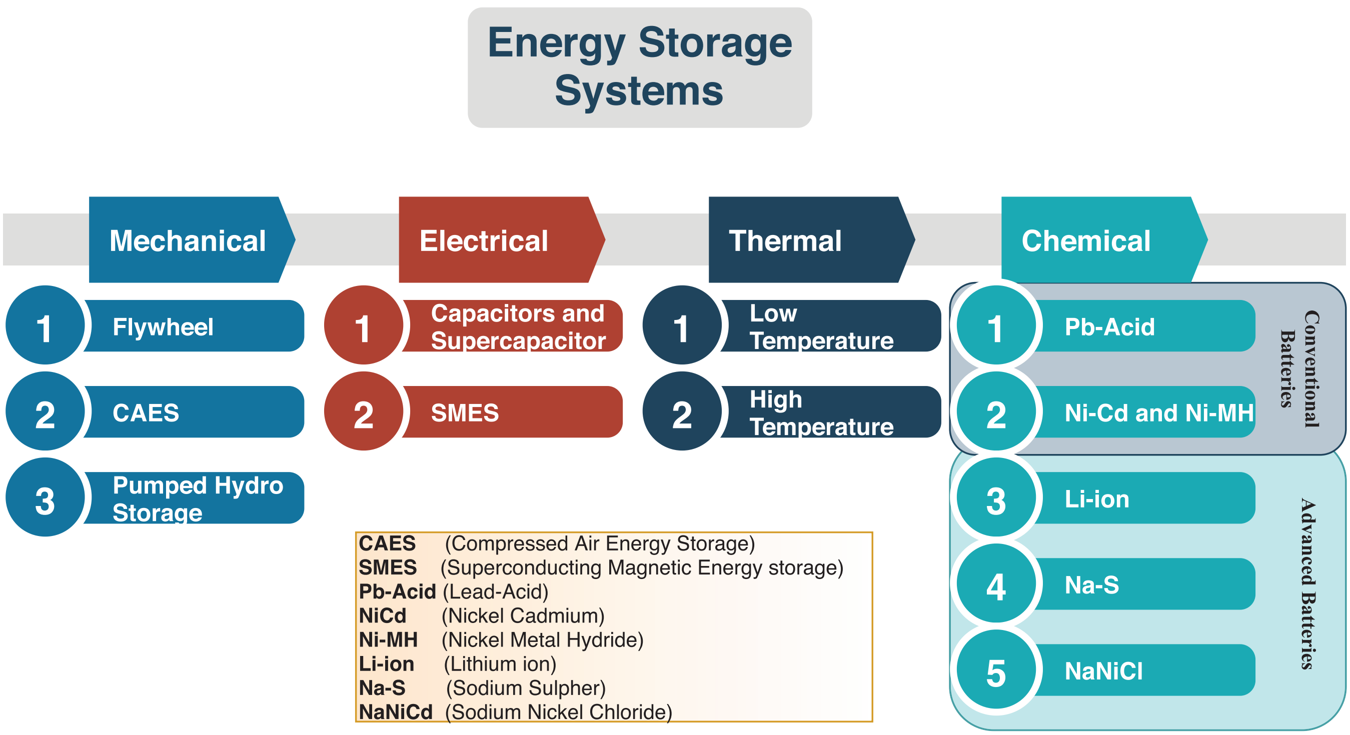


FIGURE 4 Energy storage systems

through the control of power converters. This topology allows full control of power distribution among the sources.

4.1.3 | Choice of storage option for wave energy integration

For grid integration of wave energy, the use of energy storage systems is primarily for power quality improvement and frequency regulation. To provide grid frequency stability support, low to medium capacity energy storage systems are employed for shorter periods, usually from 1–2 s by injecting and absorbing power in real-time. Modern renewable energy resources do not provide inertia support to the grid like conventional power plants. This creates an opportunity for energy storage systems to emulate this inertia response for renewable energy generating devices. For example, Parwal et al. [74] perform inertia emulation for a point absorber WEC device through a virtual excitation controller.

Grid integration studies of WEC devices can be categorised based on the storage component used:

- Grid integration of WEC with no storage component
- Grid integration of WEC with one storage component
- Grid integration of WEC with HESS

A review of these categories for grid integration studies is given in Table 6, from which it is evident that most grid integration studies use a DC link capacitor as short term storage, between back-to-back power converters. However, some use other storage systems such as super-capacitors [75], undersea storage (USS) [76] or HESS [62]. Most of the studies consider regular waves which do not represent real sea conditions. Given the strict requirements set by grid codes and the inherent variability of the resource, it is expected that the storage will play a vital role in grid integration of wave energy.

Apart from storage, the use of multiple WECs in a wave farm is an alternative for power output smoothing. Wave farm planning, through different optimisation algorithms, considering the parameters of the wave resource such as height, period and direction of wave propagation, can help reduce the inherent variability in the output power [77]. Grid integration studies have been carried out for wave farms [78] but a complete analysis considering all constraints is still absent from the literature. Similarly, the sizing of electrical components also plays an essential role in the optimised performance of wave energy devices [79].

4.2 | Control of power converters for WEC integration

Grid integration of wave energy involves power converters, which need control for proper switching action. Power converters need to be very efficient so that maximum power can be delivered to the grid. For wave energy grid integration, mostly back-to-back converters are used as shown in Table 6. This topology consists of two voltage source converters, one on the generator side (Gen-SC) and the other on the grid side (Grid-SC). The control objective of the Gen-SC is usually maximum power extraction from waves based on energy maximizing hydrodynamic control. On the other hand, Grid-SC control helps in grid synchronisation, which involves the conditions specified in the grid codes explained in Section 3. The details of various control techniques, along with the corresponding control objectives, are given in Table 6.

Most of the WEC control studies focus on Gen-SC control to extract maximum power from the waves [8, 16, 62, 80–88, 91, 92, 103–109] and substantially less consideration is given to Grid-SC control and power quality issues. It is also noted that most of the grid integration studies use simplified hydrodynamic models of WECs, which are not representative of real WECs. The grid integration studies presented in Table 6 confirm this bias, with simple PI control based pulse width modulation (PWM) is used for Grid-SC control. This is because wave energy is still at the nascent development stage, and few WEC devices are grid connected. However, the few documented grid integration studies demonstrate the importance of the use of storage systems for power quality improvement [16, 63, 75, 76]. Gen-SC control is based on the hydrodynamic control of wave energy devices, which can be broadly categorised into passive control and reactive control. The control objective of both of these controllers is to extract maximum power from waves, differ in principle. Reactive control allows bidirectional power flow between WEC and PTO to force velocity and excitation force into phase synchronisation. In contrast, passive control does not allow reactive power flow and only uses passive damping forces. A review of hydrodynamic control strategies is presented in [10]. Strategies such as complex-conjugate control [91] and phase and amplitude control[103] can also be categorised as reactive.

In [8, 80–90], the Archimedes Wave Swing (AWS) wave energy converter is studied. The AWS utilises a direct drive PTO (a linear permanent magnet generator (LPMG)) as shown in Table 5. The control objective of most of the AWS studies focus on maximum power extraction from waves through Gen-SC, and constant active power and terminal voltage through Grid-SC to provide the grid with better power quality. In [78, 91, 97, 103, 110], the advantages of using of an electric PTO, including easy control and elimination of pneumatic and hydraulic stages from the power train, and its control are discussed in detail and studies are validated by simulations and experiments. A comparison of both LPMGs and rotating permanent magnet synchronous generators is detailed in [111]. All-electric direct PTOs are also used with point absorbers, where a linear or a rotary permanent magnet generator (PMG) is used with back-to-back power converters. In [97], a rotating PMG all-electric PTO is used, and it is concluded that reactive control strategies cause overrating of electrical equipment due to increased instantaneous power. To overcome this problem, authors introduced a power saturation effect by conveniently reducing PTO applied force. However, practically, the PTO force modulation is not straightforward. A reconfigurable device is presented in [112], for which the PTO excitation force

TABLE 6 Review of power converters, their control, and energy storage for grid integration of wave energy. Note: DBR means diode bridge rectifier, BC means boost converter, B2BC means back to back converters, Gen-SC mean generator side converter, Grid-SI means grid side inverter, DBES means distributed battery energy storage system, VSC means voltage source converter, LVRT means low voltage ride-through, GSA means gravitational search algorithm, WCA means water cycle algorithm, PCC means point of common coupling, AFE means active front end, ESS means Energy storage system, MMC means Modular multilevel converter, NLVCS means non-linear vector current source, SPWM means sinusoidal pulse width modulation, MPC means Model predictive control, USS means undersea storage system, PDLSPWM means phase disposition method of level- shifted PWM, FCSMPC means finite control set model predictive control, LVRT means low voltage ride-through,FOC means field oriented control DPTC-SVM means direct power control using space vector modulation

Ref. No.	Power converter topology	Control techniques	Control Objectives	Storage Component
[8]	B2BC	Optimal Control for Gen-SC	Maximum power extraction from waves	DC link capacitor
		PI for Grid-SC	Regulate DC link voltage	
			Constant active power to the grid	
[83]	DBR			DC link capacitor
	BC	PI	DC bus voltage regulation	
	Inverter	PI	Minimize error in active power	
[82]	B2BC	PI for Gen-SC	Maximum power extraction from waves	DC link capacitor
			Generator loss minimization	
		PI for Grid-SC	Constant active power to the grid	
			Constant terminal voltage	
[84]	B2BC	Optimal control based PI for Gen-SC	Maximum power extraction from waves	DC link capacitor
	BC	PI for Grid-SC	Constant active power to the grid	DBES
			Smoothing output power through storage	
[85]	B2BC	Speed sensor-less control of LPMG for Gen-SC	Maximum power extraction from waves	DC link capacitor
		LVRT controller for Grid-SC	Fault ride-through capabilities	
			DC link voltage regulation	
[86]	Generator side AC-DC Converter	GSA based optimal PI controller	Maximum power from WEC	No storage
	DC-DC Boost Converter		Minimisation of generator loss	
			Terminal voltage maintenance of DC microgrid	
[88]	Gen-SC	WCA based optimal PI controller	Maximum power from WEC	DC link capacitor
	Grid-SI	WCA based optimal PI controller	Minimisation of generator loss	
			Terminal voltage maintenance at PCC	
[89, 90]	B2BC	Voltage oriented control	Maximum power extraction from waves	DC link capacitor
	DC-DC buck/boost converter	PI	DC link voltage regulation	Supercapacitor
[62]	B2BC	Adaptive filter based optimal control	Minimize HESS loss	Battery and Super Capacitor
	Dual active bridge converter		Smooth power supply to load	based HESS
			DC link voltage Regulation	
[91]	B2BC	Passive control	Maximum power extraction	DC link capacitor
		Trade-off control	Minimising cost per kWH	
		Complex conjugate control		
[92]	B2BC	MPC/ACC/RL Control for Gen-SC	Maximum power extraction from waves	DC link capacitor
		PI for Grid-SC	Improved global performance	
[93]	Bridge rectifier		Power quality improvement	DC link capacitor
	BC	DC voltage control	Maintain DC link voltage	
	3-level inverter	Predictive current control	Unity power factor	
[94]	Gen-SC	Passive loading	Maximum power extraction	DC link capacitor

(Continues)

TABLE 6 (Continued)

Ref. No.	Power converter topology	Control techniques	Control Objectives	Storage Component
	BC	PI	Constant DC link voltage	
	MMC	NLVCS control	Constant active power to the grid	
[63, 95]	AC/DC Rectifier		Reduction of harmonics in output power	DC link capacitor
	Voltage source inverter	PI	Power quality improvement	LCL filter
[76]	Gen-SC	Reactive control	Maximum power extraction from waves	DC link capacitor
	Storage side DC-DC converter	MPC	Control of USS and synchronous machine dynamics	USS
	MMC based isolated DC/DC converter	PDLSPWM	Power flow control	
	Grid side MMC based inverter	phase-shifted carrier-based control	Grid synchronisation	
[96]	Full bidirectional converter	Threshold control	Power extraction up to PTO limit	No storage info
		Equivalent saturation control	Grid connection impact mitigation	
[97]	B2BC	Optimum (reactive) control	Maximum power extraction from waves	
		Passive loading control		
		Field Oriented Control for Gen-SC	DC link voltage regulation	DC link capacitor
		AFE control for Grid-SC	grid synchronisation through PLL	
[16]	B2BC	Optimum control	Maximum power extraction from waves	short term ESS
		Power factor control	Active and reactive power support	
		Centralised farm control	Power quality improvement	
[75]	B2BC	Maximum power extraction control	Maximum power extraction from waves	Super-capacitor ESS
		WEC/ESS control strategy for Grid-SC	Constant power injection to grid	
	Buck-boost chopper	Low level DC chopper control	Power fluctuation compensation by ESS	
			Maintain constant DC link voltage	
[98, 99]	B2BC	FCSMPC	Speed control of air turbine	DC link capacitor
	BC		Active and reactive power control	Battery in [98]
			Energy storage power management system	Supercapacitor in [99]
[100]	B2BC	PI based FOC	Output fluctuation minimisation and LVRT	Supercapacitor
[101]	B2BC	Hysteresis band control	Active power transfer to DC bus	DC link capacitor
		PI	DC bus volatge regulation	
[102]	Grid-SC	DPTC-SVM	Pure sinusoidal currents to distorted grid	DC link capacitor

can be modulated. A geometric tool for analysis of the interplay between various constraints and control problem for wave energy converters is presented in [113].

It is evident from Table 5 that the most of the grid integration studies use point absorbers as the WEC while few focus on other devices such as OWCs in [98–100], wave surge converters in [101] and overtopping devices in [102].

4.3 | Impacts of wave energy on existing grids

Power quality is one of the main issues considering the impact of wave energy or any other renewable generation on the grid, due to the intermittency of the resource. Increasing distributed generation, and their contribution to the grid, significantly affects the ability of the power system to deliver good quality power. Because these generating stations do not usually contribute to tasks that conventional generating stations do, e.g. voltage control through reactive power, frequency control through active power control and support during grid faults. Although grid codes are now updated to incorporate these changes for wind power plants, the same will follow for wave energy as its contribution to the grid increases.

The selection of the point of grid connection will depend upon the capacity of the wave device or wave farm. For a single device, it is expected to have a connection with the distribution network rather than a high voltage transmission line connection, and its effect on the grid will not be significant enough to influence voltage and frequency control. However, its impact on the local distribution grid, in the form of small voltage variation such as harmonics induced by power converters, and flicker, may be observed. If the local grid is weak, then the flicker amplitude will be higher and can cause problems for consumers, but can be mitigated by the use of filters and energy buffers [114]. Under grid faults, the contribution from a single WEC device is not significant and cannot contribute to fault currents more than the power converter's rating. However, the use of an external static synchronous compensator (STATCOM) can help in compensation [115, 116].

In the case of wave farms connected to the grid, the first thing to consider is the connection point which will, most likely, be on the high voltage transmission system, rather than a distribution network. It is expected that they provide voltage and frequency support similar to other generating plants. Voltage source converters can provide voltage support through reactive power control. However, frequency control needs active power control, which is complicated to perform for wave energy device because the resource is highly variable and needs storage as a buffer or a backup. One way to provide this support is to design controllers for various stages of the power train (see Figure 1) and an overall centralised control, which oversees all low-level controllers and provides grid support at the point of connection [16, 96]. The effects of wave farm aggregation on power system stability for floating OWC devices are described in [117]. Three wave farm models were simulated from simplified to complete models, and the results showed that the short term transient stability could be ensured through a simplified model. Still, for long term steady-state stability, a complete model is needed. An additional consideration is the strength of the grid itself, and this is discussed by Santos et al. in [118]. Two wave farm test sites, Biscay Marine Energy Platform (BIMEP) and Atlantic Marine Energy Test Site (AMETS), were considered. BIMEP is based in Spain and connected to a strong grid, while AMETS, based in Ireland, is connected with a relatively weak grid. For the same excitation force, the impacts of a wave farm on the weaker grid was significant compared to the stronger grid connection case. The effects include lower active power and higher fluctuations in output power for AMETS, showing the importance of storage for grid integration, especially connected to a weak grid. In [119], three methods are presented to improve power quality, namely energy storage, controlled power capping, and reactive power compensation.

A detailed assessment of the impact of a wave farm at the Pacific Marine Energy Centre-South Energy Test Site (PMEC-SETS), is carried out by Armstrong et al. [120]. It is concluded that the wave farm, consisting of 10 devices, works within the specified ranges of voltage limits, flicker, and Low Voltage Ride-Through (LVRT), under the grid codes. Moreover, the impact of wave farms, with regard to short term RMS variations on the grid and rapid power fluctuations (flicker), were studied by Blavette et al. [51]. While, somewhat counter-intuitively, their results suggest that a greater number of array WECs present *more* flicker, up to a max. array of 22 WECs, the results are limited to a specific OWC array. Furthermore, the authors conclude that this trend may bit be consistent for arrays containing more than 22 elements. If sufficient storage is employed with wave farms, the flicker level, and other power quality issues, may be significantly decreased. Flicker estimation, using various assessment tools for wave farms, are discussed in [48, 49].

5 | COMBINATIONAL STUDIES

In some situations, wave energy has potential benefits over wind and solar such as better predictability and lower environmental impacts [1, 2, 5]. These benefits, and advances in offshore wind technology, have led to positive synergies between wind and wave [121–123]. The data from these studies suggests that it is advantageous to use these technologies in combination. In this regard, several studies have been conducted in the past decade, which describe the temporal complementarity between the two resources [123, 124]. The short term forecasting study of wave, wind and solar resources by Reikard et al. [125] demonstrate that wave energy can be more predictable than wind or solar, that is, the forecast error for wave at 1 h is around 5–7% as compared to wind (22%) and solar (17%). It is interesting to note that areas less effected with extremes have elevated mean values and less correlation and are ideal candidates for such combined resource exploitation [123, 126].

Solar and wave energy have been used in a study for island communities in Malaysia and the results are encouraging [127]. The use of a mix of renewable energy sources reduces the reserve requirement, compared to a single renewable energy source [125, 128]. This allows for more renewable penetration into the existing mix and emphasizes the need for combined studies. In [129], a socio-economic case for marine renewable energies as the primary source of energy for coastal communities is presented.

Wave energy can be used with either wind or solar energy depending upon the particular site characteristics, but some impediments exist. The main obstacle is the relatively low technology readiness level of wave power compared to wind and solar [130]. Lack of experience in the field of wave energy and higher insurance costs are also contributing factors to the slow development of wave energy devices. In addition, it is necessary to develop a (costly) full-scale model for combined studies and detailed analysis of the cost and performance of the system.

5.1 | Wave and solar

The solar energy resource is quotidian and has seasonal variability with the additional variability due to cloud cover. In contrast, the wave resource is generally smoother with the exception of storm events, particularly during the winter season. For this reason, wave energy can be used in conjunction with solar, especially on remote islands with an abundance of sunshine in the day time. In [131], the authors explain the importance of adding wave energy to solar energy in Karnataka, India, in terms of carbon emissions. It is concluded that the wave-solar hybrid combination is most effective in Monsoon seasons when solar resource is minimal. From an Irish perspective, a feasibility study on the use of hybrid wave and solar power determined that the temporal complementarity of both resources is ideal, due to their seasonal complementarity [132]. The additional use of storage further enhances the combination. Similarly, a study regarding optimal combinations of wind, wave and solar energy for integration into the Danish energy system is conducted by Lund [133]. After analysing various combinations, the optimal combinations are identified for different load conditions to allow for greater renewable energy penetration.

There are very few grid integration studies which consider wave and solar. Wang et al. [134] consider a grid-connected Wave-PV combination with a super-capacitor for energy storage. The WEC and PTO combination used is an AWS with an LPMG as direct drive PTO, with back-to-back converters. Dynamic stability analysis is assessed using eigenvalue and root loci analysis, and concludes that the system performs well under different irradiance levels and wave forces, while the super-capacitor removes output power fluctuations effectively. In [127], a stand-alone hybrid wave-PV combination is used with a battery energy storage system as a backup for an isolated island in Malaysia. The system is simulated under various operating conditions and produces a satisfactory steady-state response for different situations. A similar study is documented in [135], and a new power management algorithm is developed to control power flow among the sources. Eco Wave Power (EWP) installed a combined wave and solar plant in Gibraltar in a bid to commercialise their wave power technology, and it is the first grid-connected wave/solar power plant [136].

5.2 | Wave and wind

The idea of combining wave and wind energy technology is prudent, considering the rapid development of offshore wind energy technology. Combining offshore wind and wave can produce the following key benefits:

- **Reduced power variability**: Renewable sources produce variable power due to various environmental conditions. Using complementary technologies like offshore wind and wave reduces the variability of power produced [124, 137].
- **Better predictability**: The predictability of wave power is, in general, better than the wind energy. For example, one study shows that the predictability of wave energy is 23% better than wind, leading to better power output predictability for a wave energy converter (35% better than wind) [4].
- **Shared costs**: These costs may include structure costs, operations and maintenance (O&M) costs, balancing costs and shared grid infrastructure costs [130].

The prospect of using the same marine space and lowering overall environmental impacts on marine life is an additional benefit. A comprehensive review of combined wave and offshore wind technologies is presented in [138]. There are various studies on combined wave and wind resource harnessing [121–123, 139] using multiple stochastic and deterministic approaches [140, 141]. They describe the importance of using combined technologies, including increased power capacity and reduced output power variability. Combined wave and wind energy can be exploited in two ways: (1) in combined farms/arrays, but on separate platforms, and (2) by combining both technologies on the same platform, especially for offshore wind and wave.

5.2.1 | Separate platforms

Combining existing offshore wind and wave energy technology is considered in this section. These plants do not necessarily use the same support structures and may, or may not, be co-located in the same marine space and, depending upon the maritime area, are classified into independent and combined arrays [138]. Since this combination does not require any technological development due to the utilisation of developed technologies, it will only need suitable grid planning and integration. There are some studies that discuss combined wave and wind energy utilisation for electricity production and grid integration [87, 126, 142–148]. In [126], the output power variations of combined wind and wave farms are analysed, and it is demonstrated that combined utilisation is better than an individual wave or wind farms, according to the reserve requirements. In [87, 142–146], Wang et al. present various ways to integrate combined wave and wind energy with the grid. Multiple DFIGs simulate the wind farms, while multiple SCIGs simulate wave farms and grid connections use HVDC links, VSC-HVDC links, and UPFCs. The analysis shows that the proposed scheme can mitigate inherent power fluctuations. Alex et al. [147] present a similar approach to that of Wang et al., and presented UPFC with a damping controller-based grid connection, for a combined wind and wave farm, concluding that the given combination achieves dynamic stability and mitigation of power variations. A DC microgrid consisting of both wave and wind energy is proposed by Lu et al. in [148]. A battery storage system is also included in the setup, and it is concluded that the proposed method works well under sudden load changes, with the results validated by a lab-scale experimental setup.

Although the above-mentioned studies provide a case for combined exploitation of wave and wind energy resources, none of these studies consider full w2w models for the wave energy devices.

5.2.2 | Combined platforms

Combining wave and wind energy on the same platform poses a very different set of problems, compared to combining technologies on separate platforms [149]. Combined platforms can be classified in different ways [138] and an overview of hybrid wave-wind energy systems is presented in [150], which considers the addition of WECs on wind turbine platforms or by adding wind turbines on WEC platforms.

Concepts which use floating wind platforms and one or more WEC devices typically have similar stability characteristics to that of floating wind turbines. These structures can be categorised as follows [150]:

The spar: Spars are cylindrical floating structures which achieve stability through the relative position of the centre of gravity and centre of buoyancy. Most common are the Spar-Torus Combinations (STC) presented in [151–156], where a spar type wind turbine is combined with a torus-shaped heaving point absorber added at the water surface. The power performance and dynamic response of this combination are discussed in [153], and it is concluded that using combined wave and wind provides lower-cost power as compared to individual wind or wave technology, but the grid integration effects of adding a WEC on wind turbines needs further research. Another STC inspired concept include monopile wind turbines combined with wave energy devices, as presented in [157].

The barge: This simple design achieves its stability through a large surface area on the water plane. It is a low-cost design due to its simplicity [150]. Examples of such a platform combines semi-submersible floating wind turbine with a flap-type WEC [158–160].

Tensioned leg platform (TLP): This type of platform uses vertical tension mooring lines anchored to the sea bed for stability. The examples in [161, 162] use TLP supported structure wind turbine with 3 point absorbers.

WindWave float: This concept uses the Windfloat platform which uses 3 columns made up of structural beams [150], and can be combined with different WEC devices such as OWC [163], wave surge converter [164], and point absorber [165].

In addition, combinational studies which use the essential floating wave energy converter structure with additional wind turbines are also under development. Stability of the platform is achieved by hydrodynamic interaction forces between the sea surface and the platform. Examples of such devices include the Circular Hybrid Platform (C-HyP) [166], Truss Hybrid Platform (T-HyP) [167], OWC Hybrid Platform (OWC-HyP) [168], and floating power plant (P80) [169], all of which are still at the development stage.

As far as grid integration is concerned, power output assessment of some of these combinations shows that variability is reduced [153] and their integration with the grid will not be as challenging as for individual wave (or wind) energy devices. Due to the relatively low technology readiness level of wave energy, there is a long way to go before these technologies are competitive enough to be brought to market; therefore, at this time combining separate wind and wave farms are seen to be the most viable option [149].

TABLE 7 LCoE for different technologies [173, 176, 182]

Technology	LCoE (€/MWh)
Wave energy	325
Tidal energy	190
Onshore wind	67.68
Offshore wind	101.43
Combined cycle gas turbine (CCGT)	43.17
Pulverised fuel	32.57
Pressurised water reactor (PWR)	49.96

6 | VALUE OF WAVE ENERGY ON THE GRID: AN ECONOMIC CASE

One of the most essential factors in deciding whether or not a new technology is commercially viable is the cost of energy production. If wave energy is to take a share of the already competitive electricity market, the cost of energy production should be competitive to the existing technologies, such as solar and wind energy. At this stage, it is expected that the cost of wave energy production is higher than the other conversion technologies due to low technology readiness level and reservations concerning the impacts of these wave energy devices on marine life [170–172]. A comprehensive review of wave energy economics is presented in [173].

6.1 | LCoE and LVoE

LCoE is a metric to calculate the cost of energy production of a power plant, and accounts for all costs that may occur during the lifetime of the plant. There are many models available in the literature to calculate the LCoE [174], one being the discounting method which is widely used [173, 175, 176]. According to the discounting method, LCoE can be calculated as:

$$LCoE = \frac{Present\ value(costs)}{Present\ value(output)} = \frac{\sum_{t=0}^{n} C_t/(1+r)^t}{\sum_{t=0}^{n} O_t/(1+r)^t},$$

where:

C_t = Streams of real future costs in period t

O_t = Electrical outputs in period t

r = Discount rate (range for marine energy is 5%-15% [173, 176])

Both C_t and O_t are discounted back to present value. The main costs involved in wave farm plant are pre-operating costs, construction costs, operational expenditures and decommissioning costs. Details of each cost are presented in [173], including anticipated failure rates of components. Sharkey et al. [177–180] explain the costs involved in electrical components and their optimisation to reduce the LCoE of wave energy. LCoE is used to compare various energy production technologies in order to identify which technology gives the cheapest price per kilo-Watt hour (kWh). Table 7 shows comparable

LCoE values for various energy-producing technologies, and while the LCoE for various WECs is presented in [181].

Although, LCoE is an attractive approach due to its simplicity, there are problems associated with this metric such as environmental constraints, system costs and technology variations [183]. One critical problem arises when a traditional fuel-based plant (dispatchable technology) is compared with a renewable plant (non-dispatchable technology), based on LCoE. LCoE only accounts for energy produced and does not consider production profiles or the value of energy on the market [184]. An improved approach is proposed in [6], which calculates the time average as compared to the energy average in LCoE, and is known as the levelised value of energy (LVoE). Another study which uses LVoE is proposed in [185], which presents a systematic approach, based on mixed-integer linear programming, and includes environmental aspects and supply security as part of the calculation. The concept of LVoE is critical with regard to the meaningful comparison of renewable energy resources such as wave, solar and wind energy. A case study presented in [6] shows that wave energy has a positive correlation with the demand of the considered grid and has 8% more value than the solar or wind energy. It is crucial to keep in mind that it does not mean the LCoE is not a useful metric. Instead, it is a reminder that the value of energy should be considered when comparing renewable technologies.

6.2 | Capacity factor and value of wave energy on the electricity market

A practical indicator of the average load on any power plant is the capacity factor C_f and defined as the length of time a power plant operates at rated power P_r subject to a time reference [186]:

$$C_f = \frac{KWh\ generated\ in\ a\ period}{P_r \times Number\ of\ hours\ in\ that\ period}. \tag{1}$$

Capacity factors for mature technologies, such as wind and solar, have been calculated widely. For example, in Ireland, capacity factors are assessed for onshore wind at 35%, offshore wind at 45% and solar at 11%, for the year 2020 [187]. However, for wave energy, it is difficult to determine the capacity factor because of absence of commercial wave farms. However, capacity factors are estimated in some studies reviewed in [173], and depend on WEC device, location and energy conversion train. In [188], multiple locations around the globe for different wave energy technologies are considered in terms of their capacity factors. The capacity factors in those locations, for example, for Wave Dragon WEC ranges from 20%–60% in summers and 20%–70% during winter, depending upon the location. The effect of a low capacity factor on dynamic electrical ratings was studied by Sharkey et al. [189], concluding that the small capacity factors cause higher ratings of electrical devices used in grid integration which leads to higher costs of energy production. It is also suggested that low-capacity factors can cause more variability in output power and create problems for grid integration and power quality. The Joint Research Commission (JRC) ocean energy status report [190] suggested that the average capacity factor of WECs in 2020 would be 28% (maximum 41%), but it is expected that this will increase as wave energy technology matures. In the Irish electricity market, the contribution of renewable power such as wind power was traditionally included in the previous Generation Capacity Statement (GCS) adequacy studies using capacity factors [191]. However, a new approach is now used, which considers historical wind and demand data , and employs in a de-rating factor. De-rating factors include planned, and unplanned, outages and limitations on the operation and its value set by the regulatory authority, based on analysis carried out by system operators [192]. The de-rating factors for wind and solar energy are 0.103 and 0.055, respectively, according to a 2018/19 final auction information pack [193].

In addition to the sale of electricity, there are other potential economic benefits to wave energy [130]. These include the sale of the carbon credits to countries which exceed their limits [173]. Other externalities include job creation and, most importantly, improving supply security [194, 195], especially in regions heavily dependent on energy imports or with an exclusive dependence on a renewable energy source relatively uncorrelated with wave energy.

7 | CONCLUSIONS

This paper presents a comprehensive review of various aspects of grid integration of wave energy by identifying different areas which establish a frame of reference for future research. The inherent power output variability of wave energy devices present challenges for existing electric grids, and may have adverse effects on weaker grids. The availability of technology to overcome these challenges will directly influence the level of wave energy penetration into existing networks. A new classification for wave energy conversion systems, based on inertial characteristics, is crucial for grid integration studies. These inertial characteristics not only depend upon the wave energy devices but also on the type of PTO used. The importance of energy storage and efficient control of power converters for wave energy integration cannot be overstated, especially if wave farms emulate inertial characteristics imposed by the grid codes, which are expected to evolve with the inclusion of wave energy on the grid.

It can be concluded from this review that most of the grid integration studies do not fully consider the hydrodynamic characteristics of wave energy devices. Therefore, there is an urgent need to develop a complete WEC-grid model that includes all dynamic aspects of the power train, and emulates real wave characteristics. Moreover, combinational studies are vital for the rapid integration of wave energy, via resource abundance, shared costs and diversification of supply systems which leads to better supply security. Furthermore, the economic evaluation of wave energy should be broadened to include carbon emission credits, jobs creation, supply/demand profiles and other social and environmental benefits.

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