Towards modelling and control strategies for hybrid wind-wave energy converters: Challenges and opportunities

Renewable and Sustainable Energy Reviews 224 (2025) 116080

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Towards modelling and control strategies for hybrid wind-wave energy converters: Challenges and opportunities

Maria Luisa Celesti*, Giuliana Mattiazzo, Nicolás Faedo

Marine Offshore Renewable Energy Lab., Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

HIGHLIGHTS

- Overview of potential and challenges of hybrid wind-wave energy converters.
- Critical analysis of the modelling frameworks and control strategies for these systems.
- Comparison of existing approaches, highlighting strengths and limitations.
- Suggestions for future research to accelerate development and commercialisation.

ARTICLE INFO

Keywords:
Wind-wave hybrid energy systems
Optimal control
Modelling
Wave energy
Floating offshore wind turbines (FOWTs)
Hybrid platform

ABSTRACT

Hybrid wind-wave energy converters (HWWECs) offer a promising renewable energy solution by harnessing both wind and wave resources, supporting the diversification of the global energy mix. Despite their potential, HWWEC development is at an early stage, with key challenges hindering commercial availability. To reach optimal performance, HWWECs must effectively balance wind and wave energy absorption, an inherently complex task that requires accurate (yet tractable) mathematical modelling and the subsequent design of tailored control strategies, capable of handling this trade-off systematically. Aiming to shed light on the state-of-the-art of this crucial problem, this study provides a critical review of current research on modelling and control of HWWECs, focusing on the development of control-oriented dynamical models and their role in control design. Modelling is divided into key macroareas, including, *e.g.*, aerodynamics, hydrodynamics and mooring systems, common to a large class of HWWEC concepts. Given their non-traditional nature, controllers are prioritised on the wave energy converter side and categorised according to the defined performance objective. Among the key findings, this review highlights significant gaps, including a lack of a unified/generalised modelling framework, inconsistencies among similar devices when deriving control-oriented models, and a lack of development and detailed understanding of the parameterisation and solution of the associated control problem. By identifying these gaps and highlighting clear future directions, this study provides a primer for researchers seeking to enter this emerging field, contributing to accelerating the development of HWWECs and helping establish their role as a key technology in the energy transition.

1. Introduction

The population growth and the need to ensure basic living standards have increased energy requirements. This demand can not be met simply by relying on traditional energy sources such as fossil fuels, which, by raising the CO2 level, exacerbate the ongoing climate crisis [1]. As a response to this issue, the exploration of renewable energies has gained substantial success. In the quest for sustainable energy sources, offshore technologies, enabling the harnessing of energy where resources are more abundant, have made significant advancements in recent years. Among these, hybrid wind-wave energy converters (HWWECs) have attracted growing interest due to their potential to harness the synergistic benefits of wind and wave resources. Wave energy, which is a largely untapped source [2], offers significant advantages for future energy solutions, and devices that can harness both wave and wind energy simultaneously offer even greater promise. In fact, wind and wave are abundant sources [3] that often exhibit a complementary pattern, with a

* Corresponding author.
Email address: marialuisa.celesti@polito.it (M.L. Celesti).

https://doi.org/10.1016/j.rser.2025.116080
Received 13 January 2025; Received in revised form 7 July 2025; Accepted 8 July 2025
Available online 15 July 2025

Nomenclature

Abbreviations

ANN	Artificial neural network
BEM	Boundary element method
BEMT	Blade element momentum theory
CFD	Computational fluid dynamics
DLL	Dynamic-link library
DMS	Double multiple streamtube
FOWT	Floating offshore wind turbine
HWWEC	Hybrid wind-wave energy converter
HYSDEL	Hybrid systems description language
LQR	Linear quadratic regulator
MPC	Model predictive control
OWC	Oscillating water column
P	Proportional
PI	Proportional-integral
PID	Proportional-integral-derivative
PTO	Power take-off
RAO	Response amplitude operator
THP	Tuned heave plate
TLD	Tuned liquid damper
TLP	Tension leg platform
TMD	Tuned mass damper
VAWT	Vertical-axis wind turbine
WEC	Wave energy converter
WT	Wind turbine

Symbols

α_1, α_2	Mooring stiffness [N/m] and damping coefficients [Ns/m]
a	Axial induction factor
a'	Angular induction factor
β	Blade pitch angle deviation [rad]
β_1, β_2	Weighting parameters
c	Airfoil chord
c_D	Drag coefficient
c_L	Lift coefficient
c_P	Power coefficient
c_Q	Torque coefficient
c_T	Thrust coefficient
d	Disturbance vector
η	Wave free-surface elevation
ϕ	Inflow angle [rad]
F_D	Drag force [N]
f_e	Wave excitation [N]
f_h	Restoring force [N]
F_L	Lift force [N]
f_m	Mooring force [N]
F_N	Normal force [N]
F_τ	Tangential force [N]
F_T	Thrust force [N]
g_1, g_2	Stabilisation, WEC energy-maximisation functions
k_r	Radiation impulse response function [kg/s]
k_e	Excitation impulse response function [kg/s^2]
λ	Tip-speed ratio
m_∞	Added mass at infinite frequency [kg]
P	Aerodynamic power [W]
q	State vector
R	Rotor radius [m]
ρ	Wind density [kg/m^3]
r	Control volume radius [m]
s_h	Hydrostatic stiffness matrix [N/m]
T	Axial force [N]
u	Control input vector
U	Free stream wind velocity [m/s]
U_{rot}	Rotor plane wind velocity [m/s]
$x, \dot{x}, \ddot{x}$	Displacement [m], velocity [m/s], acceleration [m/s^2]
Ξ	Time interval for control optimisation
ω	Blade wake angular velocity [rad/s]
Ω	Rotor angular velocity [rad/s]

low level of correlation among different sites [4–6], and their combined use not only enhances the overall energy yield, but also provides a more stable and reliable power output [7–9], compared to the stand-alone technologies, which is crucial for meeting the growing energy demand.

One of the key advantages offered by HWWECs is the marine spatial optimisation, *i.e.*, an efficient and sustainable use of marine spaces, that aligns with various European initiatives aimed at optimising the use of marine resources and promoting sustainable energy solutions [10,11]. Additionally, HWWECs can leverage shared structures, infrastructures and mooring systems, leading to cost savings in operation and maintenance procedures [12], which are fundamental for early commercialisation.

The field of HWWECs is characterised by a wide variety of proposed concepts, ranging from fully integrated systems where wind turbines (WTs) and wave energy converters (WECs) are built into a single structure, to modular approaches, where separate devices are deployed in close proximity [13,14]. The diversity of designs reflects the complexity and novelty of these technologies. In fact, being a combination of a more mature technology (WTs) and a more recent one (WECs), which lacks a standard device/configuration, HWWECs do not yet represent a unique emerging technology [15].

Achieving efficient energy harvesting is crucial for the success of HWWECs. Adequate control system design can directly influence the reliability, efficiency and economic viability of this technology, facilitating their pathway towards commercialisation [16]. HWWECs, combining different technologies, require control objectives that can be potentially conflicting: while stability is essential for the efficient operation of WTs, WECs aim to maximise energy capture, often through increased amplitude motion, creating a conflict between the two control objectives. In fact, offshore WTs, unlike their onshore counterparts, deal with harsher environments, characterised by strong winds, waves and currents that excite the WT and the floater, increasing motion, potentially affecting power production and reducing the lifetime of the system [17].

Therefore, their control, needing to fulfil different objectives such as load reduction and platform stabilisation [18], goes beyond traditional controllers dedicated to onshore WTs. For the latter technology, the main objective is focused solely on maximising operational efficiency, including, *e.g.*, maximum power point tracking control, standard generator torque control (responsible for maximising the WT power conversion efficiency and active in the so-called operational region two (below rated wind speed) [19]), and blade pitch control (responsible for regulating the rotor speed at its rated value and active in the so-called region three (above rated wind speed)) [20–22]. On the other hand, due to the complexities that accompany hosting the turbine on a floating platform in the sea, floating offshore wind turbines (FOWTs) have extra challenges for their control system. They experience more structural loads than fixed-base turbines due to the effect of waves, *i.e.,* higher hydrodynamic loading, leading to the necessity of combining high-performance power production with stability.

Aiming at improving device stability, apart from WECs, FOWTs have been combined and complemented with different devices such as tuned mass dampers (TMDs), which consist of a suspended mass with a stiffness and a damper, tuned to the desired resonance frequency [23], and can be integrated on the nacelle [24–26] or directly into the platform [27,28]; tuned liquid dampers (TLDs), a type of TMD where the mass is replaced with liquid [29,30]; tuned heave plates (THPs), which, if properly tuned, can also produce power, (*e.g.*, using a permanent magnet linear generator [31]); active vertical vanes [32,33]; gyrostabilisers [34,35], and active mooring lines [36,37]. Nevertheless, integration with WECs seems particularly promising due to the further advantage of simultaneously harnessing wave energy, ideally enhancing the overall power output. This has motivated a trend in moving towards HWWECs, combining FOWTs and WECs [38].

An efficient exploitation of wave energy, though, requires control technology for the WEC able to pursue an energy-maximising objective, which virtually always enhances overall device motion, which contrasts with the intrinsic stabilisation needed for the WT. Therefore, an effective WEC control strategy, able to balance both platform stabilisation and wave energy-maximisation, is fundamental for the development of HWWECs. Current WEC control approaches dedicated to these devices often focus on either stabilisation of the wind system or maximisation of energy captured from waves independently, lacking the integrated perspective needed for HWWECs.

The vast majority of modern control technology available for effective (optimal) control of HWWECs (in particular, via the WEC component) is model-based, *i.e.*, a mathematical model is required for design, synthesis and tuning of controllers. These models must capture the complex interactions between wind and wave forces, the dynamic response of the platform, and the energy conversion processes of both WTs and WECs, while ideally providing a suitable tradeoff between accuracy and computational and analytical complexity. In fact, an ideal control-oriented model, useful for a wide class of real-time control technology, should capture the main dynamics of interest, describing both the wave energy conversion process and platform behaviour, in a simplified fashion, leading to structures compatible with modern control technology. The availability of such control-oriented models constitutes a key stepping stone towards improved control solutions, providing the foundation for designing controllers that can manage the multi-objective performance criteria of HWWECs, involving not only stabilisation of the platform, but also maximum wave energy extraction.

Being HWWECs technology in its infancy, standardised procedures for a systematic construction of control-oriented models do not exist to date. Yet, the availability of such mathematical structures constitutes a fundamental stepping stone towards technology design and optimisation. Motivated by the lack of a clear pathway and updated perspectives on control-oriented models and control strategies for HWWECs, this paper provides a comprehensive exploration of the evolving landscape of these systems, focusing specifically on the classification of control strategies and control-oriented modelling approaches. By providing a critical overview of the existing literature and research findings in the field, this paper aims to offer insights into the current state-of-the-art methodologies in control-oriented modelling of HWWECs, while identifying the key gaps and opportunities for further development. The systematic categorisation and examination of the different modelling approaches proposed within applied control research in the field of HWWECs, presented within this study, serve both as a framework and guideline for taking the next steps required to optimise control technology, contributing towards more efficient exploitation of wind and wave energy resources, leading the pathway towards commercialisation of these novel technologies.

The remainder of this paper is organised as follows. Section 2 gives an overview of HWWECs. In Section 3 the modelling approaches applied to describe the behaviour of these devices are detailed, and Section 4 reviews the developed control strategies found in the literature. The conclusions, along with perspectives for future work on HWWECs, are outlined in Section 5.

2. HWWECs: devices overview

As introduced within Section 1, HWWECs are innovative renewable energy systems capable of simultaneously harnessing energy from both wind and waves. By integrating offshore WTs with WECs, these systems leverage the complementary nature of wind and wave resources. This dual approach not only can increase the total energy harvested from a given location, but can also enhances the overall efficiency and reliability of the overall power generation. By sharing infrastructure and maintenance costs, HWWECs present a cost-effective solution to meeting growing energy demands while minimising environmental impacts.

Wind-wave devices are a combination of offshore wind turbines and wave energy converters and, depending on the degree of connectivity between these two technologies, they can generally be classified into co-located, hybrid, and island systems [13]. Within this study, we focus entirely on hybrid devices, which are effectively capable of integrating both technologies into a unified structure.

We begin by noting that HWWECs, being at an early stage of development, still lack a standard device [39]. In fact, even though WTs are a mature technology, when considering these as part of an offshore environment, there are many different platforms on which the WT can be effectively installed. In particular, offshore WTs can be categorised, depending on water depth, as: fixed, bottom-mounted and floating. We focus on the latter typology, as it allows access to higher wind resources in offshore areas where the bathymetry makes other typologies impractical or economically unfeasible, that can be further classified into: ballast stabilised, *e.g.*, SPAR, mooring line stabilised, *e.g.*, tension leg platform (TLP), and buoyancy stabilised, *e.g.*, barge and semi-submersibles [40–42] (see Fig. 1 for a schematic representation of FOWT platforms).

The lack of a technological convergence is even more evident when considering WECs. Nowadays, there is a wide variety of wave energy converters, and new and diverse technologies are constantly proposed, without a visible standardised design, at least in the short-term horizon. This is mainly due to the fact that there are different ways in which energy can be absorbed from the waves and, depending on the location, water depth, and purpose for which it is used, there can be different (more suitable) WEC concepts. Given the increasingly large

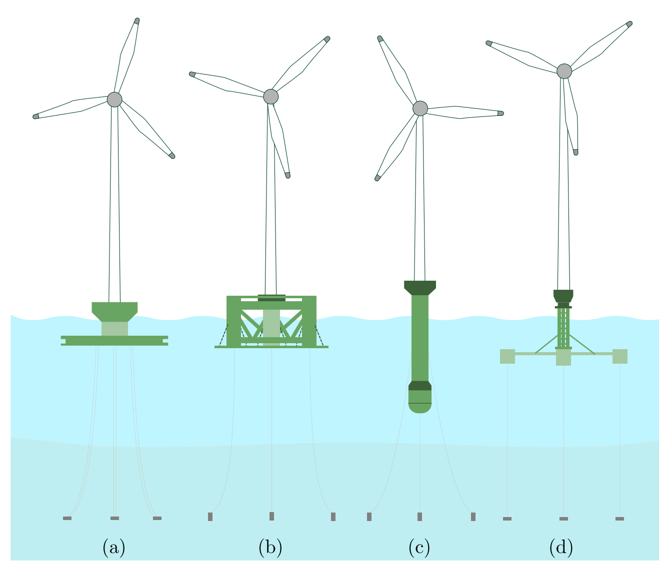

Fig. 1. Floating foundations for offshore wind turbine: (a) Barge; (b) Semi-submersible; (c) SPAR; (d) Tension leg platform.
Adapted from [43].

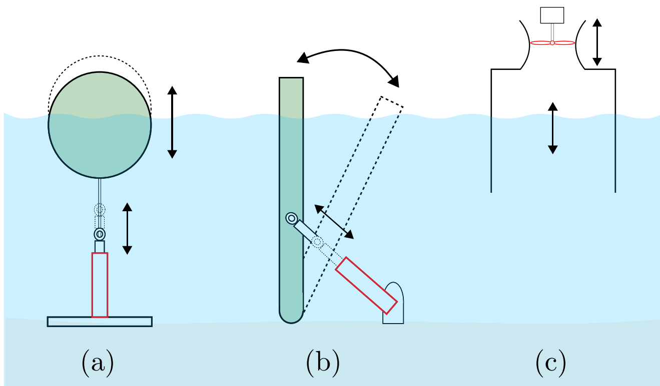

Fig. 2. Different type of WECs considered within HWWECs amongst the revised literature: (a) Point absorber; (b) Oscillating surge; (c) OWC.

number of WEC systems proposed, which can come in significantly different geometries and working principles, a number of classifications do exist within the literature [44], aiming at grouping the available conversion concepts in different ways. Following the standard classification provided by [45], WECs can be classified into oscillating water columns (OWCs), oscillating bodies, and overtopping systems. OWCs can produce energy by pushing, with a column of water varying with the incoming waves, an airflow through a bidirectional turbine [46]. Oscillating bodies, instead, encompass a large class of offshore WECs, which exploit wave regimes available in deep water. Within this family, two concepts are of particular interest, since these have been considered recursively within the literature of HWWECs: point absorbers, which have small dimensions with respect to the wavelength, are floating structures capable of absorbing energy from different directions through a motion that drives a power take-off (PTO) system [47] and; oscillating wave surge converters, which are generally comprised of a hinged deflector, positioned perpendicular to the wave direction, that moves back and forth exploiting the horizontal velocity of the wave [48]. Finally, overtopping systems capture the energy close to the wave crest by spilling into a reservoir where it is stored at a level higher than the (average) free-surface elevation. This potential energy is then used to move a turbine. Based on the classification and description provided above, Fig. 2 presents schematic representations of WECs featuring the most common working principles integrated into HWWECs studies[1] focused on modelling and control design procedures, with the PTO system highlighted in red.

The categorisation of HWWECs can be based on the specific combination of wind and wave energy technologies they employ [14,15,49]. Classifying HWWECs based on the different foundations is not simply a geometric differentiation: having different substructures means having a specific stabilising mechanism and dynamic characteristics that will influence the overall system's dynamic behaviour. Even though there is not yet a convergence to a specific device, the state-of-the-art attempts to highlight drawbacks and advantages of the existing concepts [50]. For example, in [51], considering the Italian context, a method to evaluate and classify HWWECs is proposed depending on different criteria, such as cost effectiveness, power extraction, and WEC integration, showing promising results for semi-submersible platforms.

Nowadays, this foundation type is also the one used for full-scale HWWECs. This includes, for instance, the W2POWER [52], in which a triangular semi-submersible platform, hosting two WTs at the corners, is combined with point absorbers, and the Floating Power Plant [53], with a T-shaped semi-submersible foundation (where hydrogen systems can also be incorporated), a WT on top, and an array of point absorbers. Among semi-submersible-based HWWECs, a notable device is the so-called WindWaveFloat [54], which can include different types of WECs, such as spherical point absorbers (SWEDE [55]), OWCs (installed in the columns [56]) and flaps (hinged on the three top main beams), underlying the flexibility of this device and its adaptability to different sea conditions. Both numerical and experimental analyses have been conducted to show the effect of adding WECs in terms of overall system motion and power capture. Even though the concept has been shown to be feasible and promising, there is yet no full-scale development of this system. Notable advancements of a semi-submersible hybrid concept have also been made by Bombora [57], which has successfully completed tank testing of the integration of a membrane-style WEC with a single semi-submersible floating 10 MW WT.

Taking into account ballast stabilised platforms, *i.e.*, SPAR, the spar-torus combination is the most popular [58], in which the torus (point absorber) plays a key role in meeting the tower stability requirement while increasing power extraction. Recently, a novel concept combining this type of platform with three OWCs has been proposed in [59], featuring an experimental investigation in which the synergies and advantages derived from their integration have been highlighted, showing potential in the HWWEC by increasing the overall power production without a significant adverse effect on platform motion. Finally, among HWWECs with a TLP-type platform, heaving WECs [60,61] and point absorbers [62] have been proposed for integration, analysing numerically and/or experimentally the feasibility, benefits and limitations of their combination. Representative examples of HWWECs are illustrated in Fig. 3.

Given the extensive range of existing concepts, as highlighted by the discussion provided within this section, it is crucial to emphasise that combining different devices necessitates distinct modelling approaches, taking into account various aspects and effects that may play a more or less significant role in the overall system behaviour. This requires a careful analysis and adaptation of modelling techniques and control synthesis, leveraging tailored strategies to accurately predict and optimise system performance, according to each concept. A more detailed discussion on this topic is presented in Sections 3 and 4, addressing the challenges associated with diverse device combinations.

3. HWWECs modelling for control synthesis

A proper modelling procedure is essential for accurately representing a system. "Proper" here refers to the suitability of the mathematical representation for the device, according to the desired use. The decision to include or exclude specific effects within a model can lead to markedly different outcomes, not only in terms of accuracy, but also in the time and computational resources required to produce numerical results. Consequently, even when dealing with the same system, different modelling decisions may be made depending on the specific objectives of the study and the intended use for the model. This is particularly true for HWWECs, which are inherently challenging to model due to the intricate interactions between wind and wave sub-components. In response to these complexities, this section introduces a generalised framework designed to guide the modelling task for HWWECs with particular emphasis on models for control applications, offering a comprehensive critical analysis of the control-oriented models that have been proposed and explored in the existing literature. Furthermore, a critical comparison between numerical and analytical models is offered, highlighting the limits and opportunities of different techniques from both domains. In addition to a summarising table (Table 4) that catalogues all the reviewed papers, the section includes targeted tables that highlight specific modelling aspects, as well as statistical analyses derived from this dataset. Through this analysis, strengths and limitations of different approaches are highlighted, providing valuable insights into the most effective strategies for achieving accurate and

[1] Other WEC concepts have also been considered within the larger literature of HWWEC design, see, *e.g.*, [14].

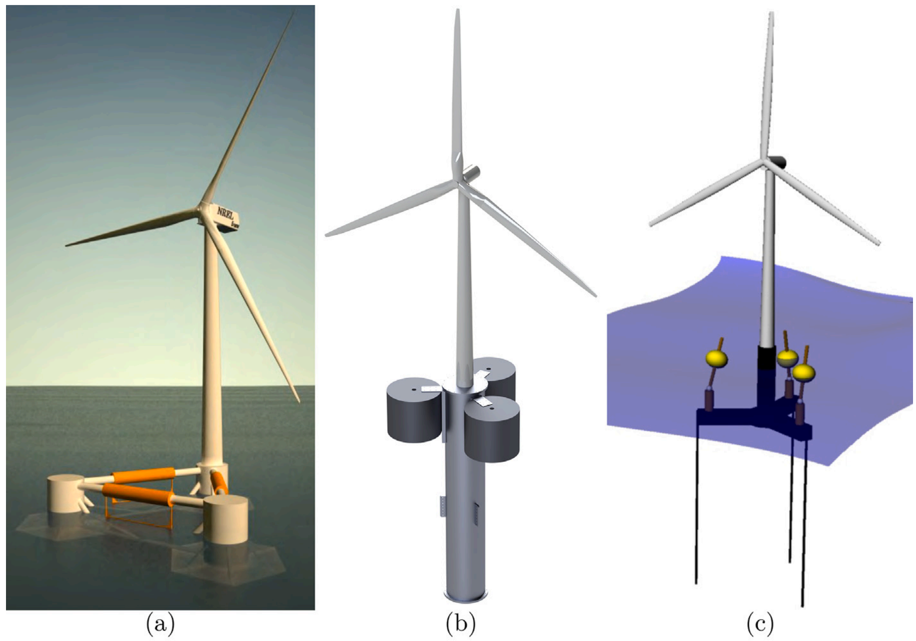

Fig. 3. Representative HWWECs amongst the revised literature: (a) Semi-submersible with flap; (b) SPAR with OWCs; (c) TLP with point absorbers. Panel (a) adapted from [54]; Panel (b) adapted from [59]; Panel (c) adapted from [62].

Table 1
Modelling frameworks for HWWECs.

Aerodynamic	Hydrodynamic	Structural dynamics	Mooring dynamics
Blade element momentum	Morison equation	Multi-body	Static/quasi-static analysis
Vortex methods	Potential flow theory	Finite element	Lumped-mass
CFD	CFD	Modal analysis	Finite element

reliable system representations for control (and overall performance optimisation) purposes.

Modelling of HWWECs can be broadly categorised into four macro areas: aerodynamic, hydrodynamic, structural analysis and mooring dynamics. Aerodynamic modelling examines the interaction between wind and the non-submerged components of the device, in particular with turbine blades, focusing on how the airflow generates forces and torques essential for turbine rotation. This aspect requires an understanding of factors such as wind speed, direction, turbulence, and blade pitch, to optimise the aerodynamic performance and ensure an efficient energy capture. Hydrodynamic modelling, meanwhile, addresses the interaction between the oceanic resource and the submerged components of the system. This involves analysing the forces and motions induced by waves, tides, and currents on the structure. Structural dynamics involve the analysis of device interactions with the loads and deformations externally applied, and the generated internal stresses and displacements, including inertia effects. Modelling this last aspect serves to ensure that the structure can withstand the harsh environmental conditions the device will face during offshore operation. Finally, mooring systems introduce another critical aspect to consider as part of the modelling process. These systems generate dynamic effects that can influence the device's stability and motion (see, *e.g.*, [63]). The interaction between mooring lines and environmental forces, such as waves, wind, and currents, adds complexity to the overall system behaviour.

Table 1 summarises the main frameworks used by the state-of-the-art literature of HWWECS, to describe aerodynamic, hydrodynamic, structural dynamics and mooring dynamics.

Each of these fields relies on a distinct set of approaches to capture the interactions between the device and its operating environment. In aerodynamic models, blade element momentum theory (BEMT) is used to estimate lift and drag forces [64], while vorticity-based methods provide more detailed wake dynamics [65]. Computational fluid dynamics allows for high-fidelity simulations of airflow around the blades. This approach is also used in hydrodynamics to solve (numerically) fine-scale interactions between water flow and the device. In modelling the water-structure interaction, alternatives are embodied by the so-called Morison equation [66] and potential flow theory. For structural dynamics, multi-body, finite element, and modal analysis techniques are used. Finally, mooring dynamics are addressed through a range of methods such as static or quasi-static analysis for simplified load estimation, lumped-mass models for time-domain simulations of line-body interactions, and finite element approaches when higher fidelity is required.

While not explicitly reported within Table 1, since it has been completely disregarded within the entirety of the revised literature, one last piece of the puzzle concerns the issue of modelling the WEC PTO system. These systems represent relevant components of the overall WEC itself, as they generate electric power from the mechanical motion of the floater (primary mover), acting also as an actuator for control implementation at the WEC level [16]. PTOs can be generally classified based on the method employed to convert the motion induced by waves into electrical power, broadly speaking [67]: hydraulic, mechanical, direct-drive, and turbines (for OWC-type WEC systems). The reader is referred to, *e.g.*, [68] for a detailed review on types and modelling of PTO systems for standalone WECs. Even though PTOs constitute an important component for the WEC, none of the studies reported herein, involving modelling and control of HWWECs, model the utilised WEC PTO system explicitly (apart from the rare exception of [69]), but only consider this as an 'ideal' block, capable of providing the exact control force required by the specific WEC controller employed. As has been shown within the larger literature of (standalone) WEC modelling and control, this modelling choice has two main consequences [70,71], which can lead to significantly different results: (a) the force/torque required by the WEC control algorithm might differ from the actual force/torque applied and, hence, re-design/tuning is often required to achieve the desired performance and; (b) considering an ideal PTO block immediately leads to assuming that the mechanical-to-electrical conversion efficiency is also ideal, *i.e.*, unitary, leaving the effect of power losses outside both the control design procedure, and the final performance assessment step. The latter (b) has deeper consequences, which can lead to a misuse of the ratio between active and reactive mechanical power by the WEC controller, requiring large peaks of bi-directional power flow, and hence a large reactive-to-active peak power ratio [71]. As a matter of fact, some extreme cases have been reported, in which ignoring the PTO model and efficiency can lead to negative average power absorption (see, *e.g.*, [72,73]), *i.e.*, the WEC becomes an overall power consumer, generated by inappropriately timed large peaks of reactive power flow.

Understanding the intricate relationships between the areas reported in Table 1 is essential to make an informed modelling decision, being aware of the considered or neglected interactions in the overall process. In fact, for control purposes, it may be ambitious to, *e.g.*, provide an exhaustive analytical description of the overall forces and loads affecting the HWWEC. The flow conditions around the air and water frame, for instance, are generally complex, thus any attempt to mathematically describe aerodynamic or hydrodynamic phenomena must result in a compromise between complexity and computational resources. Several techniques, both numerical and analytical, can be applied to model HWWECs, and an overview of the approaches currently adopted in the literature is provided in Sections 3.1 and 3.2.

We note that the modelling areas discussed above should not be viewed as isolated entities, as they are deeply interconnected and can exhibit a strong interactions. These interactions can be significant (especially under controlled conditions – see the arguments in [74]), and should be considered according to the specific objectives. Given that, within the state-of-the-art of HWWEC control, the two main objectives are energy maximisation and system stabilisation (see the discussion in Section 1), we provide, in the following, an analysis of the adopted modelling procedures having these two distinct goals in mind.

3.1. Numerical modelling techniques

Numerical modelling techniques offer a detailed and comprehensive approach to analysing HWWEC devices. These models can capture the complex coupling and interactions between WTs and wave energy converters with high precision, accounting for various environmental factors and system dynamics. This section explores the numerical modelling techniques applied in HWWECs, always focusing on studies where control is a central aspect. A broader classification of numerical techniques for HWWECs is beyond the scope of this study, and can be found in, *e.g.*, [14,15,75,76]. Note that, since the core of this study reflects the state-of-the-art of modelling for HWWECs with the scope of control design/evaluation purposes, the numerical techniques employed within the revised literature belong to the low/mid side of the fidelity spectrum, since control design and synthesis are virtually always based on models with modest computational requirements. While high-fidelity techniques, such as those based on CFD (see Table 1), can be effectively utilised to simulate both aerodynamic and hydrodynamic forces acting on the HWWEC, these come at a great computational expense (in the order of thousands of seconds per second of simulation [77]), automatically prohibiting their use in real-time control synthesis and design procedures. Nonetheless, CFD-based solvers can be effectively useful for control performance evaluation, providing a high-fidelity simulation platform for controller testing [78,79], allowing fully nonlinear aerodynamic and hydrodynamic calculations, including effects neglected by low/mid fidelity techniques (as described in Section 3.2), such as a precise account of viscosity, effects of large wave amplitudes, large floating body motion, and even vortex shedding around the WEC and structure. Finally, we also note that, in contrast to either isolated WEC systems and/or offshore wind platforms, CFD-based simulations for HWWECs come with their specific difficulties, driven by the multi-body nature of the problem itself. While beyond the scope of this study, which focuses on the literature of HWWECs with control technology development purposes, the interested reader is referred to the recent studies [80–83] for further details on the challenges and potential solutions arising in the field of CFD simulations for HWWECs.

The numerical models in the analysed studies can be established within a single computational environment or by integrating multiple numerical tools. For a comprehensive coupled dynamic analysis in wind-wave interactions, it often becomes necessary to merge tools specifically designed for different aspects of the simulation. For instance, tools such as OpenFAST [84] (previously FAST [85]), which simulate the coupled aero-hydro-servo-elastic behaviour of WTs, or AQWA [86] for hydrodynamic analysis, may need to be coupled to accurately capture the dynamic interplay between wind and wave forces. Note that several of the reviewed studies rely on earlier tools, such as FAST and AQWA, which have since been superseded by more advanced frameworks. FAST has evolved into OpenFAST, an open-source and modular tool developed by NREL, offering enhanced capabilities and broader support for simulations. Similarly, AQWA is increasingly being replaced by alternatives such as WEC-Sim, which allow for detailed time-domain modelling of WECs and support integration with control design workflows. In this context, the coupling process can be facilitated using user-defined dynamic-link libraries (DLLs), as in [87], which enable efficient communication and data exchange. Otherwise, this integration can be achieved using F2A, as in [88,89], that combines the aero-servo-elastic modelling capabilities of FAST with AQWA's strengths in non-linear hydrodynamics and mooring dynamics, enabling accurate predictions of the behaviour of HWWECs under complex environmental conditions (see [90] for a more detailed description of this tool). It is worth noting that the F2A approach originally relied on coupling FAST and AQWA, but in more recent implementations, OpenFAST and WEC-Sim are being adopted as their successors, offering improved integration and open-source accessibility.

Another approach, within the available literature, involves coupling SIMO [91] and RIFLEX [92], as shown in [93]. These tools have now been integrated into a unified modelling environment called SIMA [94], which streamlines workflows and improves model consistency. While the reviewed study still employs the legacy toolchain, SIMA is available for more efficient and comprehensive simulation of HWWECs. However, since RIFLEX models aerodynamic loads using the BEMT, when WECs are combined with vertical-axis wind turbines (VAWTs), specific tools based on the double multiple streamtube (DMS) theory are integrated for the aerodynamic analysis, as in [95], where a Darreius-type turbine is analysed [96]. The DMS model is preferred for vertical-axis WTs since it can better capture the cyclic variations, non-uniform flow, and complex wake interactions typical of VAWTs, which the BEMT cannot accurately account for. This aerodynamic model is also used in [97], and, in this case, the hydrodynamics are modelled using a MATLAB/Simulink [98] environment via the Marine Systems Simulator toolbox (described in [99]), based on the so-called Cummins equation [100]. Note that [97] does not account for WEC hydrodynamics, since no specific geometrical WEC design is actually considered.

In line with the integration of multiple numerical tools, another common approach, found in the literature, involves coupling WAMIT [101] for hydrodynamic analysis with FAST. In [102–104], this combination is used to build a dataset for data-driven training, ultimately establishing an artificial neural network-based model within the MATLAB environment. On the other hand, in [105–107], the numerical model obtained via the WAMIT-FAST coupling is directly used to develop a control strategy (see Section 4.3 for more details), which is then implemented in MATLAB. In [108,109], the modelling of OWCs dynamics and their relative control action (see Section 4.3), is established in the Simulink environment, while the dynamics of the WT are analysed, respectively,

Table 2
Summary of the numerical modelling techniques used in the analysed studies. Note that the superscript $*$ indicates open-source numerical tools.

Reference	Numerical tools	Concept
[97]	MATLAB/Simulink (Marine Systems Simulator) and DMS (in-house code)	Semi-submersible with non-declared WEC
[102]	WAMIT, FAST* and MATLAB/Simulink	Barge with OWCs
[103]	WAMIT, OpenFAST* and MATLAB/Simulink	Barge with OWCs
[88]	F2A	Semi-submersible with point absorbers
[111]	ANSYS-AQWA	Semi-submersible with point absorbers
[105]	WAMIT, FAST* and MATLAB	Barge with OWCs
[106]	WAMIT, FAST* and MATLAB	Barge with OWCs
[95]	SIMO-RIFLEX-DMS (in-house code)	SPAR with torus
[93]	SIMO-RIFLEX	Semi-submersible with torus
[104]	WAMIT, FAST* and MATLAB	Barge with OWCs
[107]	WAMIT, FAST* and MATLAB	Barge with OWCs
[108]	MOST* and MATLAB/Simulink	SPAR with OWCs
[113]	MOST*	Semi-submersible with point absorbers
[89]	F2A	Semi-submersible with point absorbers
[109]	OpenFAST* and Simulink	Semi-submersible with OWCs
[87]	FAST* and AQWA coupled using DLLs	Semi-submersible with OWCs

via MOST [110] and FAST (with the former software not accounting for structural dynamics). As in [108], the elasticity of the system is also ignored in [111], which employs ANSYS-AQWA as a single numerical modelling tool.

Table 2 summarises the numerical tools employed in the examined studies, highlighting considerable diversity in their application. This variation is partly due to the fact that different HWWECs, composed of various combinations of WECs and WTs, are being modelled, each requiring specific tools suited to their unique dynamics. As discussed in Section 2, in fact, there is not yet convergence towards a single standardised device, further complicating the selection of appropriate simulation software. Such variation in tool usage underscores the flexibility and limitations of each software depending on the specific requirements of the study both in terms of analysed device and developed control strategy. Note that Table 2 includes information regarding the open-source availability of the numerical tools used within the reviewed studies.

As a final remark, we note that a comprehensive dynamic coupling between bodies has not been explored within the literature dealing with modelling for control design and synthesis purposes. This can be ostensibly attributed to the inherent degree of complexity of modelling in a multi-body sense, increasing the computational and analytical burden of the overall HWWEC representation, precluding real-time control/efficient optimisation routines. As such, handling of body-to-body constraints in HWWECs, with the scope of control and optimisation, remains largely unexplored and an open challenge. Guidelines for achieving this objective can be taken from the broader literature (*i.e.*, studies without a control-oriented scope) in, for instance, [112], which provides a discussion on the role of constraints (in particular hinge-type) for HWWECs.

Numerical tools are invaluable for the design and analysis of HWWECs, as they facilitate the optimisation of key factors such as geometry, power performance, and dynamic behaviour. These tools can be crucial for advancing system development by providing detailed insights into performance. However, due to the complexity of HWWEC systems, some of these numerical approaches can be prohibitive for (advanced) real-time control applications, having computational requirements which can go well beyond typical controller sampling times for these devices. This underscores the importance of analytical and semi-analytical modelling techniques to implement sophisticated model-based control strategies. These approaches are described within Section 3.2.

3.2. Analytical and semi-analytical modelling techniques

Modelling HWWECs via analytical techniques can be valuable in terms of computational resources and for the implementation of specific control strategies. In fact, the computational reduction makes analytical models suitable for the development and implementation of sophisticated real-time control techniques. Furthermore, analytical models can provide closed-form solutions that allow for clear insights into system dynamics that facilitate effective control and overall device design, including, *e.g.*, internal stability, controllability and observability, both locally (about different operating points) and globally. For controller synthesis, it is desirable for the model to be as simple as possible, while still maintaining adequate accuracy, being able to represent the system behaviour according to the control objective. However, due to the complex and intricate dynamics characterising HWWECs, merging numerical and analytical methods may be beneficial for a more comprehensive device description. This is the case for semi-analytical models, which represent a mid-point between analytical and numerical techniques. This approach can leverage the strengths of analytical solutions while using numerical methods to (partially) handle the modelling task pertaining to those aspects that are difficult to model analytically. We detail, in this section, the general aspects of analytical and semi-analytical modelling of HWWECs, highlighting the key forces/effects that impact these systems, and the main underlying theoretical principles used to describe them.

3.2.1. Aerodynamics

Aerodynamic loads can be computed following different theories, including momentum theory, blade element theory or a combination of them, *i.e.*, blade element momentum theory (strip theory). BEMT is based on the assumption that the forces acting on the blade element are essentially two-dimensional. This theory can approximate well the computation of aerodynamic loads when considering a steady-state behaviour. In fact, it is the theoretical basis, with different ad-hoc corrections, for numerical tools such as AeroDyn (module of FAST and OpenFAST), MOST, and RIFLEX. This aerodynamic theory is also the most widespread method in the reviewed studies adopting an analytical/semi-analytical approach, as can be appreciated in Table 3.

BEMT merges momentum theory, originating from momentum balance on a rotating annular stream tube passing through a turbine, and blade element theory, that examines the forces generated at various sections along the blade (for further discussion on the theory, see, *e.g.*, [114,115]):

- *Momentum theory* considers the WT as a disk and analyses the momentum variation of the wind passing through it. Considering blade forces referring to a control volume (of radius r and thickness $\mathrm{d}r$), the momentum conservation brings to the following expression of the axial force:

$$\mathrm{d}T = \rho U^2 4a(1-a)\pi r \mathrm{d}r. \tag{1}$$

Considering flow field rotation, the tangential force can be obtained, leading to the following expression:

$$dQ = 4a'(1-a)\rho U \pi r^3 \Omega dr, \tag{2}$$

where U and ρ indicate, respectively, the free stream velocity and density of wind, a is the axial induction factor, *i.e.*, the fractional decrease in wind velocity between free stream and the rotor plane (computed as $a = (U - U_{rot})/U$), while $a' = \omega/2\Omega$ is the angular induction factor, with Ω and ω rotor and blade wake angular velocity, respectively.

- *Blade element theory* refers to an analysis of forces at a blade section, as a function of its geometry. Those forces, F_L (lift) and F_D (drag), can be expressed as a function of lift and drag coefficients, c_L and c_D (depending on the angle of attack), considering the relative wind velocity at the blade element, U_{rel}, and the chord, c, as

$$dF_L = c_L \frac{1}{2}\rho U_{rel}^2 c dr, \qquad dF_D = c_D \frac{1}{2}\rho U_{rel}^2 c dr, \tag{3}$$

that can be combined to obtain the forces normal, F_N, and tangential, F_τ, to the plane of rotation (indicating with ϕ the angle between the resultant velocity and the rotation plane)

$$\begin{aligned} dF_N &= dF_L \cos\phi + dF_D \sin\phi, \\ dF_\tau &= dF_L \sin\phi - dF_D \cos\phi. \end{aligned} \tag{4}$$

The combination of these two theories is not trivial, and there are different formulations to provide an effective link between them. For instance, in [116], a one-dimesional problem is formulated, approach followed also in [117]. Otherwise, loads can be computed via a blade discretisation, as in [118]. For control purposes, stationary equations are accepted as dynamically valid [119]. Therefore, thrust force, F_T acting on the entire rotor, with a radius R, and the total useful torque, T_r, can be expressed in terms of non-dimensional thrust (c_T) and torque (c_Q) coefficients, as

$$F_T = \frac{1}{2}\rho\pi R^2 c_T U^2, \qquad T_r = \frac{1}{2}\rho\pi R^3 c_Q U^2, \tag{5}$$

and the extractable power can be expressed considering the power coefficient $c_P = \lambda c_Q$ as

$$P = \frac{1}{2}\rho\pi R^2 c_P U^3. \tag{6}$$

Thrust and torque loads can be considered as lumped forces acting on the rotor blades by computing the wind speed relative to the specific point of calculation, *i.e.*, the rotor. The non-dimensional coefficients depend on parameters that determine the operating conditions of the WT, *i.e.*, blade pitch angle deviation, β, that can be also considered fixed, (*e.g.*, $\beta = 0$), and tip-speed-ratio, $\lambda = (\Omega R)/U$. These coefficients can be obtained in the form of a matrix using numerical tools, such as AeroDyn (as in [120]). For benchmark WTs, non-dimensional coefficients can be given using a simplified representation based on steady-state curves as a function of the wind velocity, method used in [121], or as look-up table, as in [122], obtained by steady-state simulation, giving a parametric approximation. Alternatively, they can be computed analytically: as reported in [123,124] various methods exist to compute a a parametric representation of c_P, that can be broadly categorised in polynomial, sinusoidal and exponential.

Within the reviewed studies, aerodynamic loads have also been considered in a more simplistic fashion, *e.g.*, being modelled as disturbances in [69,125], where they are expressed using an implicit form representation for the wave forces (in the spirit of the internal model principle of control theory [126]). A similar approach is employed in [127,128], where wind loads are modelled linearly via first-order systems as a function of wind velocity.

3.2.2. Hydrodynamics

As per aerodynamic loads, hydrodynamic forces require modelling the fluid-structure interaction. The most widely used framework for this purpose is linear potential flow theory, which assumes inviscid, irrotational, flow and can efficiently capture key hydrodynamic effects [100]. This theory is often solved using numerical tools, being a (very) widespread technique that is represented by boundary element methods (BEMs) [129], which are less computationally demanding compared to other numerical methods. These BEM algorithms provide a solution for the hydrodynamic characterisation in both the time- and frequency-domains. Among the HWWEC reviewed studies, the BEM solver WAMIT is frequently adopted, together with AQWA and OrcaWave. These solvers can be used to derive a non-parametric solution, which can later be parameterised to obtain models compatible with control design, and an overall closed-form expression. In fact, to facilitate control and design purposes, it is common to derive parametric formulations [130], e.g., via standard system identification techniques, enabling a mathematical representation of the essential dynamics of the fluid-structure interaction. As can be seen in Table 3, the majority of the reviewed papers rely on linear potential flow theory for hydrodynamics. Motivated by this, we recall, in the following, a definition of the main forces characterising this theory. The following equations (from (7) to (9)) have been summarised from [99]. Note that, even if the expressions presented here refer to a single body to streamline the exposition, these remain valid in the case of multiple interacting bodies (which is indeed the case for HWWECs).

- *Restoring forces*: arise from the difference between gravitational and buoyancy forces, and can be computed as

$$f_h = -s_h x, \tag{7}$$

Table 3
Summary of the analytical and semi-analytical modelling techniques used in the reviewed studies. N/A refers to “not available”, which indicates that the specific effect has not been considered within the modelling formulation.

Reference	Aerodynamics	Hydrodynamics	Structural dynamics	Mooring
[125]	Disturbance	Potential flow theory	N/A	N/A
[134]	N/A	Potential flow theory	N/A	N/A
[122]	BEMT	Potential flow theory	N/A	Stiffness and damping
[127]	First-order system	First-order system	Stiffness and damping	Stiffness and damping
[117]	BEMT	Morison equation	Multi-body analysis	Lumped-mass
[118]	BEMT	Potential flow theory	N/A	Stiffness
[128]	First-order system	First-order system	Stiffness and damping	Stiffness and damping
[120]	BEMT	Potential flow theory	N/A	Stiffness
[121]	BEMT	Potential flow theory	N/A	Disturbance
[69]	Disturbance	Potential flow theory	N/A	N/A
[141]	N/A	Potential flow theory	N/A	N/A
[142]	N/A	Potential flow theory	N/A	N/A

where x in $\mathbb{R}^N$ is the coordinate vector with $N \in \mathbb{N}$ indicating the degrees of freedom considered to describe the system dynamics, and $s_h \in \mathbb{R}^{N\times N}$ is the hydrostatic stiffness matrix.
- *Radiation forces*: represents the effect applied from the fluid to the body in the absence of incident waves as

$$f_r = -m_\infty \ddot{x} - \dot{x} * k_r, \tag{8}$$

where $m_\infty \in \mathbb{R}^{N\times N}$ represents the so-called added mass at infinity frequency, while $k_r(t) \in \mathbb{R}^{N\times N}$ is the radiation impulse function, expressing any coupling due to radiation between different modes of motion via the off-diagonal terms. Within the manuscript, the operator $*$ indicates convolution. Both m_∞ and k_r can be derived using BEMs or panel methods [131], and a parametric representation can be obtained via system identification [132,133].
- *Wave excitation:* describes the effect of waves acting on a fixed "ghost" body, and can be expressed as follows:

$$f_e = \eta * k_e, \tag{9}$$

where η is the free-surface elevation, while $k_e(t) \in \mathbb{R}^{N\times N}$ is the excitation impulse response function arising from superposition of the so-called dynamic (linear) Froude-Krylov and diffraction forces, and can be computed via BEM solvers. By way of example, in [134], this force is approximated via a linear model consisting of a polynomial expression with coefficients tuned via system identification, and multiplied by a delayed wave function, linearised via first-order Padè-approximation. In contrast, in [122], the wave excitation is computed based on the response amplitude operator, while [125] considers f_e as a disturbance.

The combination of these effects, along with the control action, is commonly referred to as "Cummins' equation" and it is the basis for control-oriented modelling of the hydrodynamic loads on floating systems. A detailed discussion on Cummins' equation in the context of WECs can be found in, *e.g.*, [16,100]. In HWWECs, modelled following an analytical approach, linear potential flow theory is used in all the reviewed studies with only a few exceptions. In fact, in some cases, a linear description is not representative and non-linear effects have to be taken into account to give a more reliable description of the device behaviour. In order to provide a more complete description of the hydrodynamics, uncertainty models can be added. An example of this for WECs can be found in [135], in which a linear description for the uncertainty is proposed, in order to "cover" any unmodelled effect (that can also be nonlinear). In [117], Cummins' formulation is broadened with an additional term representing viscous effects, generated by shear stress by means of the so-called Morison equation [66]. Instead, in [127,128], as per the aerodynamics, wave loads are described linearly via first-order systems (filters) as a function of wave height.

3.2.3. Structural dynamics

In HWWECs, structural dynamics refers to the behaviour of both WEC and WT components such as blades, tower, and drivetrain under dynamic loads. Considering structural dynamics is fundamental for models focused on load management and device survivability, such as in fatigue analysis, or when designing for extreme wind-wave conditions. However, when the control objective is maximising energy output from the WEC or stabilising the WT, as per the majority of the reviewed studies (as further specified in Section 4), detailed modelling of structural dynamics may not be essential. In these cases, control strategies can often rely on simplified models without needing to capture the full complexity of the structural dynamic response. Therefore, rigid-body theory, neglecting flexibility effects of device components, is considered accurate enough to represent the floating wind turbine [136] and WEC dynamics.

However, the assumption of modelling the entire WT as a single rigid body can be overly simplistic for certain HWWEC systems. This is especially true for configurations where the cross-sectional area of the tower differs significantly from that of the substructure. In such cases, the system behaviour can be compared to a cantilever beam, and additional effects need to be accounted for. As per [127,128], where the substructure is of a barge type, and structural dynamics are accounted for via a stiffness-damping model and an extra degree of freedom. HWWECs can be analytically modelled via a multi-body approach, *e.g.*, using Kane's method, as in [117], where the scope is to offer a generic framework and therefore to consider all the load effects, including structural dynamics. Moreover, a broader trend towards higher-capacity FOWTs, such as 15 MW-class machines, is also emerging in recent HWWEC concepts [14,137]. In such configurations, structural dynamics become more critical due to pronounced aeroelastic effects, and hence neglecting these may lead to unrealistic evaluations of both the overall system and controller performances. While these considerations are important for larger systems, the majority of current HWWEC control studies remain focused on smaller-scale systems (e.g., 5 MW WT), which ostensibly explains the absence of this modelling macroarea when addressing control-oriented modelling and subsequent control design.

3.2.4. Mooring dynamics

Mooring systems play a key role in maintaining offshore platform stability and performance. These systems are subjected to dynamic environmental forces from waves, wind, and currents, which necessitate accurate yet computationally efficient modelling for both design and control purposes. A common approach for mooring dynamics suitable for control purposes, is represented by static modelling that neglects inertia forces and drag loads, representing the mooring system through a linear spring-damper framework. This simplified model assumes mooring loads can be described as a restoring force, which responds to the device displacement. The force can be computed as:

$$f_m = \alpha_1 x + \alpha_2 \dot{x}, \tag{10}$$

where $\{\alpha_1, \alpha_2\} \subset \mathbb{R}^{N\times N}$ are, respectively, the stiffness and damping coefficients. The reported formulation is based on principles discussed in [138]. This method provides a computationally efficient alternative to more complex approaches, such as multi-body and quasi-static methods, and it can be employed independently of the different types of mooring, *i.e.*, for both catenary and tensioned lines. In the reviewed studies, this approach is the most-wide spread, though some of the literature only considers the stiffness action [118,120], *i.e.*, $\alpha_2 == 0$ in (10). In [122], both restoring and damping effects are considered, and the coefficients are derived via the MAP + + solver [139]. A multi-body approach, *i.e.*, lumped-mass, is instead used in [117], consistently with the overall presented model. Comprehensive reviews of mooring systems for WECs and offshore WTs (in a standalone fashion) are provided in [36,140], respectively.

Table 3 presents a summary of the techniques used in the reviewed studies using an analytical/semi-analytical approach, across the key modelling areas discussed in this section, *i.e.*, aerodynamics, hydrodynamics, structural dynamics and moorings. In line with this categorisation, Fig. 4 offers a comparison between numerical and analytical/semi-analytical methods, illustrating the percentage of reviewed studies effectively considering each of the discussed areas within their corresponding HWWEC modelling procedure.

The radar plot in Fig. 4 clearly shows that numerical techniques address a wider range of aspects, compared to analytical/semi-analytical approaches. This suggests that certain dynamics are more challenging to model analytically, leading to the omission of those aspects that are less likely to significantly impact the results. This ostensibly leads researchers to make use of numerical techniques (most of which are readily available – see Table 2), as opposed to deriving analytical expressions representing each of the modelling areas involved. We note that fully numerical techniques, which can provide high-fidelity models, can be used to validate models derived analytically, or to test developed control algorithms as simulation platforms, as in [69,117,122]. Alternatively, model validation can be obtained experimentally, as in [89].

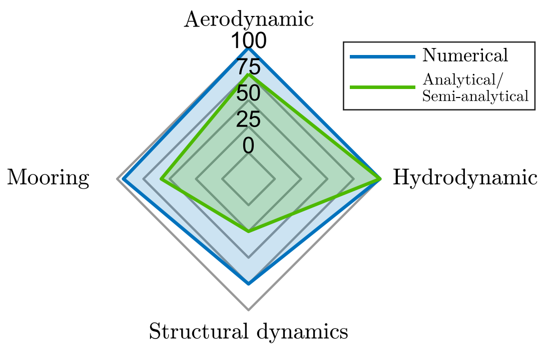

Fig. 4. Percentage of studies, modelled with numerical and analytical/semi-analytical techniques, that consider a specific modelling effect.

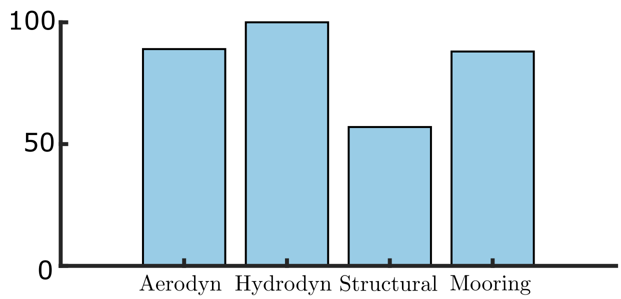

Fig. 5. Overall percentage of modelled effects within numerical and analytical/semi-analytical methods. Data extracted from Table 4, based on the classification of 28 reviewed papers in the core topic.

We stress, once again, that the level of modelling detail ultimately depends on the specific application and its objectives. For control purposes, it is not always necessary to capture every aspect in full detail, as some factors may be less critical or can be modelled with simplified assumptions (or even omitted), without compromising reliability and performance. In contrast, certain aspects might require a more detailed approach, depending on their influence on system behaviour under controlled conditions.

Fig. 5 reports the percentage of reviewed papers addressing control of HWWEC that model each main modelling area, further highlighting that hydrodynamic loads are consistently considered across all the papers, whether using a numerical or analytical/semi-analytical approach. The high focus on hydrodynamics reflects the fact that these models are primarily developed to design effective controllers for the WEC, where accurate representation of wave-structure interaction is essential for achieving optimal performance. The inclusion of other areas, such as mooring, structural dynamics, and aerodynamics, depends largely on the specific goals of the study. It is important to note that a more comprehensive model offers deeper insights and enables more sophisticated analyses. However, at the same time, the control strategies implemented within these detailed numerical models tend to be more "simple" compared to their analytical counterparts, which often employ more advanced control techniques, as further discussed in Section 4.

4. Control techniques for HWWECs

Control of HWWECs, with a combination of wind and wave harnessing technology, presents a complex problem, with a plurality of objectives, including maximising captured power (referring either to the WEC, the WT, or both subsystems via separate control strategies), and platform stabilisation. Within this hybrid configuration, each component, *i.e.*, WT and WEC, pursues individually, potentially conflicting control objectives, as discussed at length within Section 1. We note that our focus is exclusively on control strategies applied to WECs (which are effectively the less developed yet highly innovative element within the hybrid domain), while specific WT control (being much more mature) remains outside the scope of this analysis.

As a matter of fact, the potential for WECs in HWWECs relies not only on capturing extra energy from waves, but also on the potential to aid in stabilising the floating structure, helping in recreating almost onshore conditions for the wind turbine, facilitating the use of well-established and commercially available WT control technology. Nonetheless, the joint contribution of FOWTs and WECs to the stabilisation of HWWEC systems may offer additional benefits and could be worth further exploration in future studies, following the lines of recent advances in floating offshore wind, *e.g.*, [143]. In fact, control systems for FOWTs, adapted from those used in onshore and fixed-bottom turbines, are designed to overcome the high structural loads and complex hydrodynamic forces present in marine environments (see Section 1). FOWT control strategies, therefore, prioritise stabilisation to reduce platform motion. On the other hand, the control problem for WECs seeks to maximise converted energy, and this often results in large amplitude motion [16].

The energy available in ocean waves varies over time due to changes in wave height, wave period, and wave direction. Therefore, WECs must be able to adjust their motion in response to the changing wave conditions to capture as much energy as possible. Adequate control technology is hence crucial to ensure maximum energy extraction from ocean waves, with efficient controllers being able to improve reliability and reduce the levelised cost of wave energy [16], making HWWECs more appealing for commercialisation. In the following, WEC control strategies for HWWECs are reviewed and compared critically by analysing the approaches considered in current state-of-the-art of HWWEC control, exploring how each study has addressed (or not) the underlying challenges.

This section retraces the standard path to implement a controller, which begins with the design phase, where the objectives and structure of the controller are defined, followed by the synthesis phase, which, along with tuning, determines how control parameters are computed, and their final values. Therefore, the discussion covers the definition of control objectives and explores both optimal and non-optimal approaches for design and synthesis, as well as techniques for tuning the control parameters, used within the state-of-the-art. Note that, while not present within the state-of-the-art, ostensibly due to the current lack of technology convergence, HWWEC systems (as per the case of standalone WECs) also necessitate supervisory control techniques in the case of extreme wave events. These controllers, which enter into play in the so-called "survival mode" [144], do not focus on improving device conversion performance but instead attempt to protect the overall device from unrecoverable damage in the case of extreme conditions. The interested reader is referred to, for instance [144, 145], for further discussion on supervisory control for standalone WEC systems.

4.1. WEC control objective

As previously discussed, when dealing with HWWECs, the WEC controller may be designed to aim for different objectives, *i.e.*, platform stability and/or wave energy capture maximisation. In WECs, energy maximisation is achieved by tuning the resonance frequency to match that characterising the sea-state. This tuning often enhances the WEC movement which, being structurally connected to the platform, can lead to an increase in motion amplitude for the overall system, contrasting with the platform stability requirement for the WT. Only a few studies attempt to address both objectives, while others prefer to focus only on a single design function, as can be seen in the pie chart in Fig. 6, which reports the percentage of analysed studies pursuing each WEC control objective.

The chart shows that most studies focus on achieving stabilisation through the WEC control action. This trend aligns with the role of

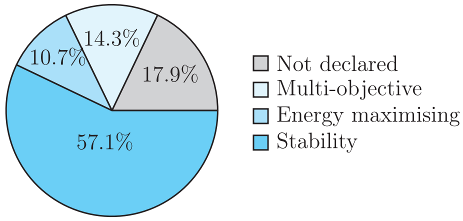

Fig. 6. WEC control objective in HWWECs: category percentage of the analysed work. Data extracted from Table 4, based on the classification of 28 reviewed papers in the core topic.

WECs that, as specified in Section 1, are largely used as extra stabilising components for FOWTs. In other words, stabilisation is preferred over energy-maximisation in the current state-of-the-art, going directly in contrast with the standard control objective for stand-alone WECs. In these studies focusing on stabilisation, various indicators are used to assess platform motion performance. While there is no unified metric across the literature, common measures include platform pitch amplitude, (*e.g.*, [103,125]), root mean square motion, (*e.g.*, [141]), spectral analysis of platform response, (*e.g.*, [95]), and response amplitude operators, (*e.g.*, [97]).

As highlighted in Fig. 6, there is a substantial number of studies in which the control objective is not declared. The control action is implemented in the model without defining a clear control objective. In these studies, authors investigate both platform motion and WEC-produced power by mere simulation, without a proper definition of control objective (and hence an actual measure of its achievement). Another aspect confirmed by Fig. 6, is that, within the state-of-the-art, only a limited number of studies have attempted to address both energy-maximising and stabilising objectives together, *i.e.*, in a multi-objective fashion. It is important to note that the reported percentage of studies with multi-objective control highlights the fact that this domain remains virtually unexplored, as can be seen in Table 4, partially addressed in only 4 papers. In the context of this novel field, this underscores an existing gap that necessitates a systematic approach to be effectively addressed.

Following the description of control objectives, different WEC control techniques have been adopted in the reviewed HWWEC studies to effectively tackle design and synthesis. These approaches are further analysed and generally categorised as optimal control, in Section 4.2, followed by non-optimal control, in Section 4.3.

4.2. Optimal control approaches

Within this study, and customary with standard theory in the field [146], we refer to optimal controllers as those model-based techniques relying on a mathematical description of the system dynamics to predict the value of the objective function over a certain time period. This model is essential for computing the control inputs required to optimise the desired performance criteria, and can be expressed, in a general way, by the following equation:

$$\dot{q} = f(q, d, u), \tag{11}$$

where $q \in \mathbb{R}^n$ is the so-called state vector, $d \in \mathbb{R}^p$ denotes disturbances or external influences, while $u \in \mathbb{R}^m$ is the control input vector, all related by the state-transition function $f : \mathbb{R}^n \times \mathbb{R}^p \times \mathbb{R}^m \to \mathbb{R}^n$. The unifying feature of optimal control is the employment of an analytical objective function that is involved in a constrained or unconstrained minimisation (or maximisation) procedure, which can be solved via different techniques. In HWWECs, optimal control strategies are not yet extensively applied, and the optimal control problem is mostly used to obtain platform stabilisation or in a multi-objective context, where the control action seeks both energy maximisation and stabilisation. Therefore, the optimal control problem for these devices can be generally defined as follows,

Optimal control problem

$$\begin{aligned} &\min \int_{\Xi} (\beta_1 g_1 + \beta_2 g_2)\mathrm{d}t \\ &\textbf{subject to:} \\ &\dot{q} = f(q, d, u), \\ &\text{state and input constraints,} \end{aligned} \tag{12}$$

where Ξ describes the (time-domain) set in which the optimisation is performed, $\{g_1, g_2\}$ represent, respectively, the stabilisation and WEC energy-maximisation functions (or a proxy for them), while $\{\beta_1, \beta_2\}$ represent weighting parameters. Note that equation (12) effectively describes a family of control objective functions for the WEC in terms of the maps defined via g_1 (platform stabilisation) and g_2 (WEC energy maximisation). Furthermore, the family (12) is parameterised in terms of two variables, β_1 and β_2, which are effectively used in practice to define a suitable trade-off between the two objectives g_1 and g_2, according to the dynamics and constraints of the specific HWWEC under consideration. The extreme cases effectively correspond with (standard) single-objective optimisation, *i.e.*, $\beta_1 = 1$ and $\beta_2 = 0$ implies a platform stabilisation objective for the WEC controller, while $\beta_1 = 0$ and $\beta_2 = 1$ implies a purely WEC energy maximisation objective. Beyond these extreme cases, the values for β_1 and β_2 can be effectively used to solve the multi-objective control problem, leading to the computation of a suitable Pareto front for (12), following the standard weighted-sum method [147].

Among the revised studies, in the category of optimal approaches, together with techniques traditionally considered optimal such as MPC, H_∞ and LQR, we also include controllers with a limited parametric structure, whose values are defined via an optimisation. This is the case of [113,120], in which the parameters of a proportional-integral (PI) controller are defined via an optimisation procedure, aiming at nacelle acceleration minimisation and energy maximisation for the former, and energy cost reduction in the case of the latter. In these optimisations, solved via a tailored optimisation algorithm compared with other standard techniques in [120] (where same values for proportional and integral parameters are assumed) and non-derivative Nelder-Mead methods in [113], geometric parameters are also included, trying to offer a comprehensive analysis, yet opting for overly simplistic control parameterisations. Instead, in [69], a non-dominated sorted genetic algorithm [148] is employed to optimise the hydraulic PTO system only (four parameters), with minimum platform motion and maximum energy absorption as objective functions, and maximum motion and minimum power as state constraints.

Studies leveraging more standard (and complete) optimal control approaches include model predictive control (MPC) structures, as those employed in, *e.g.*, [121,122,125]. MPC, capable of handling system constraints and considering future behaviour in a receding-horizon fashion, is a well-established control strategy in the WEC domain [149], and is also consequently adapted for HWWECs. This control strategy, with control force constraints, is implemented to pursue stabilisation in [150], where the HWWEC is compared to an inverted pendulum. In [125], platform motion (in terms of pitch position and velocity), is minimised subject to constraints in maximum PTO force, with the current state obtained via a state-observer based on standard Kalman filtering techniques [151]. The system with constraints is modelled in a mixed logical framework via hybrid systems description language [152].

Force constraints are also included in [122], where roll and pitch platform motion are minimised ignoring external loads in the prediction sequences, hence avoiding the necessity of implementing combined estimation and forecasting methodologies for the wave excitation (see, *e.g.*, [153]). In [121], the MPC structure is used to obtain a multi-objective control action pursuing wave energy capture maximisation and platform stabilisation. The control action is composed of a feedback term involving the state vector, and a feed-forward term including the estimation

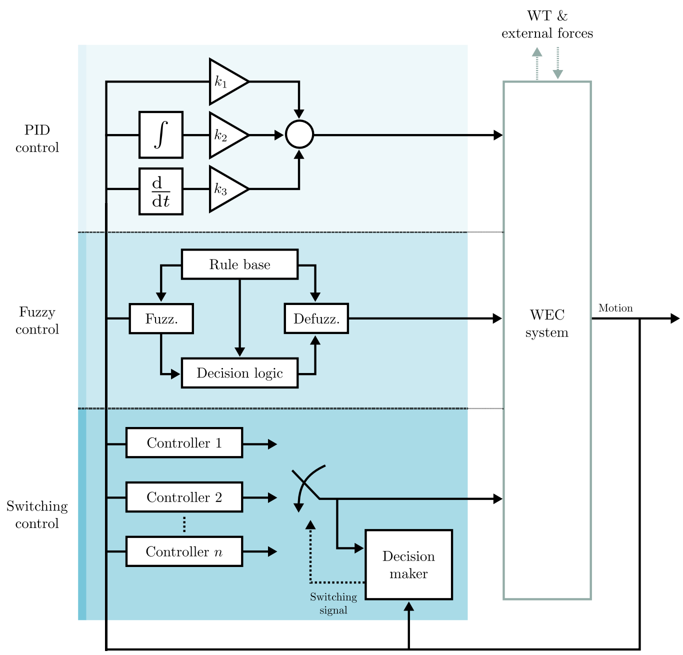

Fig. 7. Overview of non-optimal WEC control strategies commonly applied to HWWECs. Note that each block represents a generalised form of its respective control approach. For instance, in the PID control block, the gains k_1, k_2, and k_3 may be omitted depending on the implementation, resulting in simplified (e.g., passive or reactive) control behaviour.

and prediction (with a finite horizon coupled with an infinite control horizon to ensure solution uniqueness and closed-loop stability [154]) of the incoming wave excitation performed, respectively, via a Kalman filter estimator and an autoregressive model [155].

A multi-objective controller is also proposed in [142], where an LQR structure is adopted to balance platform stability and energy maximisation. However, the formulation in [142] is not capable of handling (hard) constraints. Finally, in [134], an H_∞ control strategy is developed to minimise platform motion under constraints regarding the mass, spring and damper of the suspension system, which is considered as a generic WEC.

4.3. Non-optimal control approaches

Within this section, we consider the control strategies which do not fall under the definition of optimal (as per Section 4.2). These techniques are designed to manage processes without the explicit definition of an associated optimal control problem, but rely on simpler methods, with milder computational requirements, that prioritise ease of implementation. In HWWECs, several key types of non-optimal control strategies are implemented, including: switching control, fuzzy logic control and gain scheduling. Other studies, instead, define and compute control parameters leveraging a heuristic approach, relying on intuitive rules derived from experience or experimentation, rather than a formal mathematical model. These non-optimal WEC control strategies are schematically illustrated in Fig. 7, which presents representative control architectures commonly implemented for HWWECs within the revised literature.

In several studies within the available literature, a *switching* control strategy is implemented, where different control laws or parameters are dynamically alternated based on specific system and/or environmental conditions (considered by a decision making algorithm), as schematically shown in Fig. 7. Note that this strategy does not inherently guarantee crucial system properties such as stability. In [105–107], platform motion minimisation is obtained by means of a switching control law that regulates the opening and closure of OWC valves based on response amplitude operators (RAOs). In particular, in [106], the RAOs of platform pitch and fore-aft motion with closed and open OWCs are measured to inform the switching control while, in [105,107], where the same device is analysed, the control law is defined taking into account platform pitch RAOs and wind speed, defining a switching point for the valves opening and closure. This control strategy is also adopted in other studies analysing HWWEC devices with OWCs. In [127], the airflow is regulated via two PID controllers (one for each OWC integrated into the platform) that are activated alternately based on the platform pitch motion. A switching control strategy for OWCs is also investigated experimentally in [156], based on chamber pressure and platform pitch velocity.

Outside the domain of HWWECs integrated with OWCs, [88] implements a switching strategy, based on platform pitch velocity and relative velocity between WEC and platform, offering a comparison with a benchmark linear damping controller. The PTO damping coefficient is set equal to the frequency-dependent hydrodynamic damping for the passive control strategy, while in the switching controller (which is of a bang-bang type [146]), this value switches between the hydrodynamic damping and twice its value.

Another control strategy falling within the non-optimal category, implemented for HWWECs, is *fuzzy logic control*. It relies on a fuzzification–defuzzification process, where a rule base and decision logic determine the system response, as illustrated in Fig. 7, being able to provide control signals without needing an accurate analytical model of the system. In fact, this strategy is implemented in [102,103], where the HWWEC is modelled via an artificial neural network trained with data obtained from a numerical model. The control architecture is defined in terms of a feedback loop, aiming at platform stability, with platform pitch and its derivative as measurable variables, regulating the valve plate opening angle of the OWCs. On the other hand, in [128], a mathematical model for the HWWEC is derived, and the adequate opening and closing of OWCs valves is controlled with a fuzzy controller, with standard membership functions, having as inputs the error between platform pitch and a reference value (and corresponding error derivative). A different control strategy mitigating abrupt valve opening associated with switching control is developed in [109], where a continuous valve opening is enabled depending on the chamber pressure and platform pitch and roll velocity.

Within HWWECs, two well-known controller structures are widely considered, *i.e.*, *passive (proportional) and reactive (proportional-integral)* controllers, schematically reported in Fig. 7. The computation of the control parameters has been achieved, within the literature, via different strategies, also including empirical procedures. In [97], the parameters of a PI controller are varied in a discrete manner within pre-selected ranges, together with the mass of a hypothetical WEC, trying to identify an "ideal" device for the considered hybrid system. A parametric study of the damping coefficient within a PI controller is conducted in [95], investigating different values of damping with a fixed stiffness, selecting the value that yields greater wave power production. A similar procedure is carried out in [93], with the same type of WEC as in the previous study, *i.e.*, a torus point absorber, but in a configuration involving multiple WECs rather than a single device. In [89], where a Coulomb damping model is assumed for the PTO system, the PTO force is changed when the relative velocity between WEC and platform is zero, using different values.

Other studies derive the proportional-integral parameters via a frequency-dependent formulation. In [118], the authors define a damping coefficient to optimise energy produced by a gyroscopic WEC [157], but actually aim for stability. In this numerical simulation, the enhanced stability is ostensibly limited to the analysed sea states and cannot be, in general, concluded for other wave conditions. In [104], control parameters are defined following the formulation presented in [56], with the dissipative (damping) term proportional to OWC volume chamber variation and the reactive term proportional to volume rate change. Finally, in [141], a PI structure, changing with the operating condition, is implemented to achieve energy maximisation, based on the impedance-matching principle. Meanwhile, a passive system is proposed in [117], where great effort has been dedicated to the model. In [87], a comparison between two kinds of active feedback control strategies, *i.e.*, switching control and continuous gain-scheduling, and a passive linear damping controller with a series of selected parameters, is performed. The switching between different control configurations is determined by the sign of the product of the platform pitching velocity and air pressure in the OWC chamber. In the continuous gain-scheduling approach, gains are adjusted as a function of operating conditions or system parameters, allowing the controller to adapt dynamically to different conditions. This is used to overcome potentially complex behaviour due to the two-state switching, with threshold values defined for platform velocity to determine different control scenarios. A comparison of benchmark control schemes is also performed in [111], where linear damping, reactive and spring damping controllers are implemented, with control parameters defined based on hydrodynamic coefficients (according to [158]). In particular, the PTO damping is set equal to the hydrodynamic damping, while the reactive/spring term depends on the added inertia and hydrostatic restoring coefficient. Finally, in [108], OWCs PTO control is expressed by a standard power law, adopted to limit the rotational speed of the OWC air turbine to avoid generator overpower.

4.4. On model complexity and control solution space

To accurately represent HWWECs, complex models that detail the intricate device-environment interactions are often needed, as discussed in Section 3. However, to achieve and implement optimal control strategies (as per Section 4.2), analytical models, likely less comprehensive than numerical models (see Fig. 4), are necessary. This poses a gap that remains unresolved, as the simplifications needed for optimal control may overlook critical dynamics captured in higher-fidelity numerical models.

Some studies develop a higher-fidelity model that is then adapted for control design. There are various techniques that can be used to reduce the complexity of controller design, including model reduction (see, *e.g.*, [159]) and/or linearisation around an equilibrium state, as in [122]. In [125], the control synthesis is based on a model developed using hybrid systems description language (HYSDEL) [152] while, in [121], a control-oriented model is developed starting from a non-linear description. Finally, in [69], the multi-objective optimisation is performed on an ANN (artificial neural network) surrogate model.

Nonetheless, bridging the gap between model accuracy and control feasibility is an ongoing challenge in the field, without a clear winning solution able to balance model complexity with effective controller implementation. Within the state-of-the-art, in fact, it is more likely to find a prioritisation of one of these two aspects: either the use of less detailed models paired with optimal control strategies, or more comprehensive models with simpler control approaches. This trade-off highlights the difficulty in balancing model complexity with the requirements for an effective and implementable control strategy.

This trend is clearly visible in Fig. 8, where the proportion of optimal and non-optimal based control strategies is reported, across "model completeness" in the analysed studies. In particular, four different levels of model completeness are defined within this paper, based on the number of macro areas considered (as outlined in Section 3). These levels range from red, representing a model with only one area considered, to green, indicating a model that includes all four areas. The intermediate levels include orange, which corresponds to a model considering two areas, and yellow, representing a model that includes three areas. Each bar in Fig. 8 is divided to show the proportion of studies employing optimal (dark-shaded) versus non-optimal (light-shaded) techniques. Notably, there is a higher percentage of studies using optimal techniques at lower levels of model completeness, indicating a shift in methodological rigour as model completeness increases.

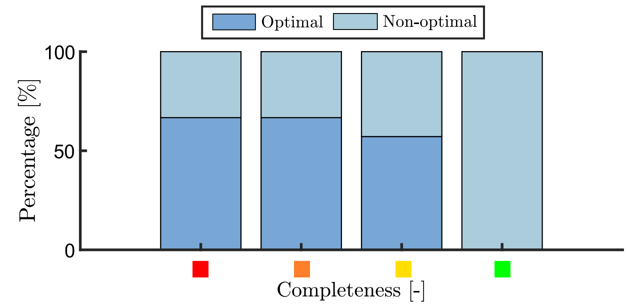

Fig. 8. Percentage of optimal and non-optimal control strategies at varying levels of model completeness. Number of considered macro areas in the model: ■ = 1; ■ = 2; ■ = 3; ■ = 4.

5. Perspectives and future directions

HWWECs represent a promising technology that can play a crucial role in the advancement of the clean energy transition. By capturing energy from both wind and waves, these systems can leverage complementary renewable sources, resulting in more consistent and reliable power output compared to standalone technologies. Utilising shared marine space and infrastructure, hybrid converters can also reduce operational costs, optimising space and resources in marine environments. This integrated approach not only enhances energy efficiency but also offers a pathway to more cost-effective renewable energy solutions, making HWWECs a key technology in achieving sustainable energy goals.

However, HWWECs are not yet commercially viable, partly due to the lack of a standardised technology. Currently, no universal design (let alone a mathematical modelling procedure and associated control solution) has yet been established as standard, meaning that each developed system requires custom solutions, which can increase costs and complicate development. This lack of standardisation also makes it challenging to have a consistent framework for evaluating device performance and reliability. Establishing a standard design and model can constitute a critical step towards scaling production, moving HWWECs closer to commercial readiness.

Control technology has a fundamental role to play in aiding this transition, yet it brings significant technical challenges to the table. Specifically, the stabilisation requirements for the WT often conflict with the need to maximise wave energy capture in HWWECs. While a multi-objective control approach could help balance these competing demands, only a limited number of studies have explored this strategy (with limited parameterisations), and even fewer have investigated standard optimal control techniques. This is ostensibly due to the intrinsic complexity in formulating (and balancing) the associated optimal control problem for HWWECs, given the degree of interaction between the different modelling areas (see Section 3). The development of reliable control frameworks is hence an essential (yet missing) stepping stone to advance HWWECs towards efficient performance.

In order to provide a critical comparison between the revised studies, concerning both modelling approach and control strategies, Table 4 provides the reader with a comprehensive summary of the main characteristics highlighted and discussed throughout this review. The identified challenges are clearly highlighted and summarised within Table 4, showing a plethora of different WEC-platform combinations (lack of standardisation), and a scarcity of both multi-objective and optimal controllers.

On the modelling side, analytical approaches, which are fundamental for adequate synthesis of optimal control strategies (and analysis of key dynamical properties), are often overly simplistic. This is ostensibly due to the complexities arising from fluid-system interactions

Table 4
Summary of main characteristics of the reviewed studies, highlighting key objectives and approaches. Abbreviations: S = stability; E = energy maximisation; SO = single-objective; MO = multi-objective; Opt. = optimal; N = numerical; M = mathematical. Number of considered macro areas in the model: 🟥 = 1; 🟧 = 2; 🟨 = 3; 🟩 = 4.

Reference	WEC type	Platform type	Control strategy	Control objective			Opt.	Model approach		Model completeness
				SO		MO				
				S	E			N	M	
[97]	N/A	Semi-submersible	Reactive (PI)	•			×	•		🟧
[125]	Point-absorber	Semi-submersible	MPC	•			✓		•	🟧
[134]	Point-absorber	Semi-submersible	H_∞	•			✓		•	🟥
[122]	Point-absorbers	Semi-submersible	MPC	•			✓		•	🟨
[102]	OWCs	Barge	Fuzzy logic	•			×	•		🟩
[103]	OWCs	Barge	Fuzzy logic	•			×	•		🟩
[88]	Point-absorbers	Semi-submersible	Bang-bang (P)	•			×	•		🟩
[111]	Point-absorbers	Semi-submersible	Passive/Reactive				×	•		🟨
[105]	OWCs	Barge	Switching (PI)	•			×	•		🟩
[106]	OWCs	Barge	Switching (PI)	•			×	•		🟩
[127]	OWCs	Barge	PID	•			×		•	🟩
[117]	Torus	SPAR	Passive (P)	•			×		•	🟩
[118]	Gyroscopic	Seaflower	Reactive (PI)		•		×		•	🟨
[128]	OWCs	Barge	Fuzzy logic	•			×		•	🟩
[95]	Torus	SPAR	Reactive (PI)				×	•		🟩
[93]	Torus	Semi-submersible	Reactive (PI)				×	•		🟩
[104]	OWCs	Barge	Reactive (PI)	•			×	•		🟩
[120]	Torus	Semi-submersible	Reactive (PI)			•	✓		•	🟨
[107]	OWCs	Barge	Switching	•			×	•		🟩
[108]	OWCs	SPAR	Power law				×	•		🟨
[113]	Point-absorbers	Semi-submersible	Reactive (PI)		•		✓	•		🟨
[121]	Point-absorbers	Semi-submersible	MPC			•	✓		•	🟨
[69]	Point-absorbers	Semi-submersible	Passive			•	✓		•	🟧
[89]	Point-absorbers	Semi-submersible	Switching				×	•		🟩
[109]	OWCs	Semi-submersible	Switching	•			×	•		🟩
[87]	OWCs	Semi-submersible	Passive (P)	•			×	•		🟩
[141]	Flap	Semi-submersible	Reactive (PI)		•		×		•	🟥
[142]	Flap	Semi-submersible	LQR			•	✓		•	🟥

(and the corresponding sub-components) in HWWECs, which require simplifying assumptions for analytical derivation, adding a degree of uncertainty to the developed model. A valid alternative, to describe the system behaviour, is represented by data-based control-oriented modelling, which exploits techniques from the system identification field. This approach has been adopted within the standalone WEC literature (with some success, see [160]), and can be extended analogously to the case of HWWECs. Furthermore, following recent trends in the field of (standalone) floating offshore wind [161], coupled physical-numerical models can provide a "mid-point" alternative, in which system (experimental) data is combined with a subset of numerical solvers, potentially being able to offer a parsimonious model, useful for model-based control purposes.

One of the main challenges that HWWECs are facing for control, as extensively discussed within this study, is the need for a multi-objective control strategy balancing platform motion reduction and wave energy capture maximisation. Integrating these objectives within a unified control framework can effectively address this challenge. Tuning control gains to heuristically balance these two objectives may be time-consuming and strongly dependent on expert knowledge and/or the specific resource (wind/wave/current) conditions. Therefore, employing optimal control strategies characterised by a systematic design procedure, rather than controllers with parameters set in a non-optimal manner, can significantly enhance system performance. Particularly, optimal controllers able to handle constraints in real-time are essential to avoid performance degradation, and ensure the overall safe operation of the system (reducing maintenance costs).

Finally, an additional approach, that could significantly benefit the development of HWWECs, is a suitable integrative design framework, such as control co-design [162], to explore a broader range of interventions for altering the overall system dynamics. While some studies examine the impact of structural design changes on HWWECs dynamics, (*e.g.*, [89,163,164]), there remains a gap in holistic approaches that integrate control and structural design within a unified process. Control co-design is already widely adopted in many research areas, such as standalone WTs [165], and a first example of its application to HWWECs is provided in [166]. These systems, composed of interacting subsystems, are suitable candidates for control co-design, and can significantly benefit from this technique.

Declaration of competing interest

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

Acknowledgements

Project funded by the European Union - NextGenerationEU under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.2 | Project code: MSCA2024_0000032 - CUP: E13C25001010006 – Project title: Unlocking wave power: Economic-aware control co-design for wave energy conversion (ECOWAVE).

Data availability

No data were used for the research described in the article.

References

[1] Kose N, Bekun FV, Alola AA. Criticality of sustainable research and development-led growth in EU: the role of renewable and non-renewable energy. Environ Sci Pollut Res 2020;27(11):12683–91.
[2] Gunn K, Stock-Williams C. Quantifying the global wave power resource. Renew Energy 2012;44:296–304.
[3] Robertson B, Dunkle G, Gadasi J, Garcia-Medina G, Yang Z. Holistic marine energy resource assessments: a wave and offshore wind perspective of metocean conditions. Renew Energy 2021;170:286–301.
[4] Johannessen K, Meling TS, Hayer S. Joint distribution for wind and waves in the northern north sea. In: ISOPE international ocean and polar engineering conference; ISOPE; 2001, pp. ISOPE–I.

[5] Rusu L, Ganea D, Mereuta E. A joint evaluation of wave and wind energy resources in the Black sea based on 20-year hindcast information. Energy Explor Exploit 2018;36(2):335–51.
[6] Fusco F, Nolan G, Ringwood JV. Variability reduction through optimal combination of wind/wave resources–an Irish case study. Energy 2010;35(1):314–25.
[7] Gao Q, Khan SS, Sergiienko N, Ertugrul N, Hemer M, Negnevitsky M, et al. Assessment of wind and wave power characteristic and potential for hybrid exploration in Australia. Renew Sustain Energy Rev 2022;168:112747.
[8] Görmüş T, Aydoğan B, Ayat B. Analysis of hybrid exploitation of wind and wave power in the Mediterranean and the Black Sea. Energy Convers Manag 2024;299:117820.
[9] Vázquez R, Cabos W, Nieto-Borge JC, Gutiérrez C. Complementarity of offshore energy resources on the Spanish coasts: wind, wave, and photovoltaic energy. Renew Energy 2024;224:120213.
[10] Schaefer N, Barale V. Maritime spatial planning: opportunities & challenges in the framework of the EU integrated maritime policy. J Coast Conserv 2011;15:237–45.
[11] Zaucha J, Gee K. Maritime spatial planning: past, present, future. Springer Nature; 2019.
[12] Astariz S, Perez-Collazo C, Abanades J, Iglesias G. Towards the optimal design of a co-located wind-wave farm. Energy 2015;84:15–24.
[13] Pérez-Collazo C, Greaves D, Iglesias G. A review of combined wave and offshore wind energy. Renew Sustain Energy Rev 2015;42:141–53.
[14] Wan L, Moan T, Gao Z, Shi W. A review on the technical development of combined wind and wave energy conversion systems. Energy 2024:130885.
[15] Dong X, Li Y, Li D, Cao F, Jiang X, Shi H. A state-of-the-art review of the hybrid wind-wave energy converter. Prog Energy 2022;4(4):042004.
[16] Ringwood JV, Zhan S, Faedo N. Empowering wave energy with control technology: possibilities and pitfalls. Annu Rev Control 2023;55:18-44.
[17] Porchetta S, Muñoz-Esparza D, Munters W, van Beeck J, van Lipzig N. Impact of ocean waves on offshore wind farm power production. Renew Energy 2021;180:1179–93.
[18] López-Queija J, Robles E, Jugo J, Alonso-Quesada S. Review of control technologies for floating offshore wind turbines. Renew Sustain Energy Rev 2022;167:112787.
[19] Pao LY, Johnson KE. Control of wind turbines. IEEE Control Syst Mag 2011;31(2):44–62.
[20] Njiri JG, Söffker D. State-of-the-art in wind turbine control: trends and challenges. Renew Sustain Energy Rev 2016;60:377–93.
[21] Apata O, Oyedokun DTO. An overview of control techniques for wind turbine systems. Sci Afr 2020;10:e00566.
[22] Menezes EJN, Araújo AM, Da Silva NSB. A review on wind turbine control and its associated methods. J Clean Prod 2018;174:945–53.
[23] Gutierrez Soto M, Adeli H. Tuned mass dampers. Arch Comput Methods Eng 2013;20:419–31.
[24] He E-M, Hu Y-Q, Zhang Y. Optimization design of tuned mass damper for vibration suppression of a barge-type offshore floating wind turbine. Proc Inst Mech Eng Part M J Eng Marit Environ 2017;231(1):302–15.
[25] Dinh V-N, Basu B. Passive control of floating offshore wind turbine nacelle and spar vibrations by multiple tuned mass dampers. Struct Control Health Monit 2015;22(1):152–76.
[26] Stewart G, Lackner M. Offshore wind turbine load reduction employing optimal passive tuned mass damping systems. IEEE Trans Control Syst Technol 2013;21(4):1090–104.
[27] Si Y, Karimi HR, Gao H. Modelling and optimization of a passive structural control design for a spar-type floating wind turbine. Eng Struct 2014;69:168–82.
[28] Zhang Y, Zhao X, Wei X. Robust structural control of an underactuated floating wind turbine. Wind Energy 2020;23(12):2166–85.
[29] Tong X, Zhao X, Karcanias A. Passive vibration control of an offshore floating hydrostatic wind turbine model. Wind Energy 2018;21(9):697–714.
[30] Coudurier C, Lepreux O, Petit N. Passive and semi-active control of an offshore floating wind turbine using a tuned liquid column damper. IFAC-PapersOnLine 2015;48(16):241–47.
[31] Liu K, Ou J. A novel tuned heave plate system for heave motion suppression and energy harvesting on semi-submersible platforms. Sci China Technol Sci 2016;59:897–912.
[32] Yang Z, Li Y. Active vertical vane control for stabilizing platform roll motion of floating offshore turbines. Wind Energy 2018;21(11):997–1010.
[33] Jalili K, Li Y, Rotea MA. Pitch and roll motion control of a floating wind turbine with hybrid actuation. In: Dynamic systems and control conference; vol. 46193. American Society of Mechanical Engineers; 2014, p. V002T18A005.
[34] Palraj M, Rajamanickam P. Motion control of a barge for offshore wind turbine (OWT) using gyrostabilizer. Ocean Eng 2020;209:107500.
[35] Cheng P, Yang X, Wan D. Motion control of a semi-submersible platform for offshore wind turbines using gyrostabilizer. In: ISOPE international ocean and polar engineering conference; ISOPE; 2024, pp. ISOPE–I.
[36] Borg M, Collu M, Kolios A. Offshore floating vertical axis wind turbines, dynamics modelling state of the art. Part II: Mooring line and structural dynamics. Renew Sustain Energy Rev 2014;39:1226–34.
[37] Li Y, Wu Z. Stabilization of floating offshore wind turbines by artificial muscle based active mooring line force control. In: 2016 American control conference (ACC); IEEE; 2016. p. 2277–82.
[38] Edwards EC, Holcombe A, Brown S, Ransley E, Hann M, Greaves D. Trends in floating offshore wind platforms: a review of early-stage devices. Renew Sustain Energy Rev 2024;193:114271.
[39] Gao Q, Ertugrul N, Ding B, Negnevitsky M. Offshore wind, wave and integrated energy conversion systems: a review and future. In: 2020 Australasian universities power engineering conference (AUPEC); IEEE; 2020. p. 1–6.
[40] Thiagarajan KP, Dagher HJ. A review of floating platform concepts for offshore wind energy generation. J Offshore Mech Arctic Eng 2014;136(2):020903.
[41] Wang X, Zeng X, Li J, Yang X, Wang H. A review on recent advancements of substructures for offshore wind turbines. Energy Convers Manag 2018;158:103–19.
[42] Wu X, Hu Y, Li Y, Yang J, Duan L, Wang T, et al. Foundations of offshore wind turbines: a review. Renew Sustain Energy Rev 2019;104:379–93.
[43] Iberdrola. Floating offshore wind power: a milestone to boost renewables through innovation; 2024, https://www.iberdrola.com/innovation/floating-offshore-wind. [Accessed: 16/07/2024].
[44] Pecher A, Kofoed JP. Handbook of ocean wave energy. Springer Nature; 2017.
[45] Falcao AFDO. Wave energy utilization: a review of the technologies. Renew Sustain Energy Rev 2010;14(3):899–918.
[46] Falcão AFO, Henriques JCC. Oscillating-water-column wave energy converters and air turbines: a review. Renew Energy 2016;85:1391–424.
[47] Guo B, Wang T, Jin S, Duan S, Yang K, Zhao Y. A review of point absorber wave energy converters. J Mar Sci Eng 2022;10(10):1534.
[48] Drew B, Plummer AR, Sahinkaya MN. A review of wave energy converter technology. 2009.
[49] Saeidtehrani S, Fazeres-Ferradosa T, Rosa-Santos P, Taveira-Pinto F. Review on floating wave-wind energy converter plants: nonlinear dynamic assessment tools. Sustain Energy Technol Assess 2022;54:102753.
[50] Tomey-Bozo N, Murphy J, Lewis T, Thomas G. A review and comparison of offshore floating concepts with combined wind-wave energy. In: Proc 11th Eur wave tidal energy conf., vol. 1; 2015.
[51] Petracca E, Sirigu M, Issoglio D, Ghigo A, Bracco G. Techno-economic designs of hybrid wind-wave offshore energy systems and comparison with topsis analysis: an Italian case study. J Phys Conf Ser 2024;2767(5):052067.
[52] Hanssen JE, Margheritini L, O'Sullivan K, Mayorga P, Martinez I, Arriaga A, et al. Design and performance validation of a hybrid offshore renewable energy platform. In: 2015 tenth international conference on ecological vehicles and renewable energies (EVER); IEEE; 2015. p. 1–8.
[53] Plant FP. Floating power plant technology; 2024. https://floatingpowerplant.com/technology/. [Accessed: 18/07/2024].
[54] Weinstein A, Roddier D, Banister K. WindWaveFloat (WWF): final scientific report. Tech. Rep. United States: Principle Power Inc.; 2012.
[55] Peiffer A, Roddier D, Aubault A. Design of a point absorber inside the WindFloat structure. In: International conference on offshore mechanics and arctic engineering, vol. 44373; 2011. p. 247–55.
[56] Aubault A, Alves M, Sarmento AN, Roddier D, Peiffer A. Modeling of an oscillating water column on the floating foundation WindFloat. In: International conference on offshore mechanics and arctic engineering, vol. 44373; 2011. p. 235–46.
[57] Bomborawave. Bombora wind wave integration; 2024. https://bomborawave.com/mwave-platforms/. [Accessed: 19/07/2024].
[58] Muliawan MJ, Karimirad M, Moan T. Dynamic response and power performance of a combined spar-type floating wind turbine and coaxial floating wave energy converter. Renew Energy 2013;50:47–57.
[59] Fenu B, Bonfanti M, Bardazzi A, Pilloton C, Lucarelli A, Mattiazzo G. Experimental investigation of a multi-owc wind turbine floating platform. Ocean Eng 2023;281:114619.
[60] Zhou M-R, Pan Y, Ren N-X, Zhu Y. Operational performance of a combined TLP-type floating wind turbine and heave-type floating wave energy converter system. In: 2nd 2016 international conference on sustainable development (ICSD 2016); Atlantis Press; 2016. p. 341–45.
[61] Ren N, Ma Z, Shan B, Ning D, Ou J. Experimental and numerical study of dynamic responses of a new combined TLP type floating wind turbine and a wave energy converter under operational conditions. Renew Energy 2020;151:966–74.
[62] Bachynski EE, Moan T. Point absorber design for a combined wind and wave energy converter on a tension-leg support structure. In: International conference on offshore mechanics and arctic engineering, vol. 55423. American Society of Mechanical Engineers; 2013, p. V008T09A025.
[63] Papini G, Paduano B, Pasta E, Carapellese F, Mattiazzo G, Faedo N. On the influence of mooring systems in optimal predictive control for wave energy converters. Renew Energy 2023;218:119242.
[64] Hansen M. Aerodynamics of wind turbines. Routledge; 2015.
[65] Branlard E. Wind turbine aerodynamics and vorticity-based methods: fundamentals and recent applications. Springer; 2017.
[66] Morison JR, Johnson JW, Schaaf SA. The force exerted by surface waves on piles. J Petrol Technol 1950;2(5):149–54.
[67] Carapellese F, Paduano B, Faedo N, et al. Performance optimisation of wave energy converters. Ref Module Earth Syst Environ Sci 2024.
[68] Penalba M, Ringwood JV. A review of wave-to-wire models for wave energy converters. Energies 2016;9(7):506.
[69] Huang S, Wang J, Yang M, Dong G, Wang Y, Liu Y. Parameter analysis and dual-objective optimization of the hydraulic power take-off system of a floating wind-wave hybrid system. Ocean Eng 2024;307:118058.
[70] Sergiienko NY, Bacelli G, Coe RG, Cazzolato BS. A comparison of efficiency-aware model-predictive control approaches for wave energy devices. J Ocean Eng Mar Energy 2022:1–13.
[71] Said HA, García-Violini D, Faedo N, Ringwood JV. On the ratio of reactive to active power in wave energy converter control. IEEE Open J Control Syst 2023;3:14–31.
[72] Faedo N, Giorgi G, Ringwood JV, Mattiazzo G. Nonlinear moment-based optimal control of wave energy converters with non-ideal power take-off systems. In: International conference on offshore mechanics and arctic engineering; vol. 85932. American Society of Mechanical Engineers; 2022, p. V008T09A082.
[73] Bacelli G, Genest R, Ringwood JV. Nonlinear control of flap-type wave energy converter with a non-ideal power take-off system. Annu Rev Control 2015;40:116–26.

[74] Windt C, Faedo N, Penalba M, Dias F, Ringwood JV. Reactive control of wave energy devices–the modelling paradox. Appl Ocean Res 2021;109:102574.
[75] Cao F, Yu M, Liu B, Wei Z, Xue L, Han M, et al. Progress of combined wind and wave energy harvesting devices and related coupling simulation techniques. J Mar Sci Eng 2023;11(1):212.
[76] Hallak TS, Gaspar JF, Soares CG. Numerical modelling of floating wind-wave platforms. In: Innovations in renewable energies offshore. CRC Press; 2025. p. 815–24.
[77] Ferziger JH, Perić M, Street RL. Computational methods for fluid dynamics. springer; 2019.
[78] Penalba M, Davidson J, Windt C, Ringwood JV. A high-fidelity wave-to-wire simulation platform for wave energy converters: coupled numerical wave tank and power take-off models. Appl Energy 2018;226:655–69.
[79] Windt C, Davidson J, Ransley EJ, Greaves D, Jakobsen M, Kramer M, et al. Validation of a cfd-based numerical wave tank model for the power production assessment of the wavestar ocean wave energy converter. Renew Energy 2020;146:2499–516.
[80] Cheng Y, Liu W, Dai S, Yuan Z, Incecik A. Wave energy conversion by multi-mode exciting wave energy converters arrayed around a floating platform. Energy 2024;313:133621.
[81] Campaña-Alonso G, Martín-San-Román R, Méndez-López B, Benito-Cia P, Azcona-Armendáriz J. Of 2: coupling OpenFAST and OpenFOAM for high-fidelity aero-hydro-servo-elastic FOWT simulations. Wind Energy Science 2023;8(10):1597–611.
[82] Kim YJ, Charlou M, Bouscasse B, Leroy V, Aliyar S, Bonnefoy F, et al. High fidelity simulations of a floating offshore wind turbine in irregular waves by coupling OpenFOAM and OpenFAST. Renew Energy 2025:122486.
[83] Xu Z, Liu Y, Wei C, Wang D, Xue G. Hydrodynamic analysis and optimisation of a novel wind-wave hybrid system combined with the semi-submersible platform and various wave energy converters. Energy 2025:136697.
[84] National Renewable Energy Laboratory. OpenFAST user documentation. National Renewable Energy Laboratory; 2025. Available: https://openfast.readthedocs.io/en/dev/source/user/index.html. [Online]. [Accessed: 2025-05-26].
[85] Jonkman JM, Buhl ML, et al. FAST user's guide, vol. 365. Golden, CO, USA: National Renewable Energy Laboratory; 2005.
[86] Ansys A. AQWA theory manual. Canonsburg, PA, USA: AQWA; 2013.
[87] Zhang D, Chen Z, Liu X, Sun J, Yu H, Zeng W, et al. A coupled numerical framework for hybrid floating offshore wind turbine and oscillating water column wave energy converters. Energy Convers Manag 2022;267:115933.
[88] Chen Z, Yu J, Sun J, Tan M, Yang S, Ying Y, et al. Load reduction of semi-submersible floating wind turbines by integrating heaving-type wave energy converters with bang-bang control. Front Energy Res 2022;10:929307.
[89] Chen Z, Sun J, Yang J, Sun Y, Chen Q, Zhao H, et al. Experimental and numerical analysis of power take-off control effects on the dynamic performance of a floating wind-wave combined system. Renew Energy 2024;226:120353.
[90] Yang Y, Bashir M, Michailides C, Li C, Wang J. Development and application of an aero-hydro-servo-elastic coupling framework for analysis of floating offshore wind turbines. Renew Energy 2020;161:606–25.
[91] Sintef O. Simo 4.23.0 theory manual. Trondheim, Norway: SINTEF Ocean; 2022.
[92] Fylling I, Larsen CM, Sødahl N, Passano E, Bech A, Engseth AG, et al. Riflex user's manual, MARINTEK report, Trondheim, 1998.
[93] Li Y, Ong MC, Wang K, Li L, Cheng Z. Power performance and dynamic responses of an integrated system with a semi-submersible wind turbine and four torus-shaped wave energy converters. Ocean Eng 2022;259:111810.
[94] SINTEF Ocean. Sima documentation. Trondheim, Norway: SINTEF Ocean, 2022.
[95] Cheng Z, Wen TR, Ong MC, Wang K. Power performance and dynamic responses of a combined floating vertical axis wind turbine and wave energy converter concept. Energy 2019;171:190–204.
[96] Paulsen US, Vita L, Madsen HA, Hattel J, Ritchie E, Leban KM, et al. 1st DeepWind 5 MW baseline design. Energy Procedia 2012;24:27–35.
[97] Borg M, Collu M, Brennan FP. Use of a wave energy converter as a motion suppression device for floating wind turbines. Energy Procedia 2013;35:223–33.
[98] T. M. Inc. MATLAB. Natick, Massachusetts, United States: T. M. Inc. [Online]. Available: https://www.mathworks.com
[99] Fossen TI. Handbook of marine craft hydrodynamics and motion control. John Willy & Sons Ltd; 2011.
[100] Falnes J, Kurniawan A. Ocean waves and oscillating systems: linear interactions including wave-energy extraction, vol. 8. Cambridge University Press; 2020.
[101] Wamit I, et al. Wamit user manual, vol. 527. Chestnut Hill, MA, USA: WAMIT Inc.; 2006.
[102] Ahmad I, M'Zoughi F, Aboutalebi P, Garrido I, Garrido AJ. Enhancing stability and performance of hybrid offshore wind platforms: a novel fuzzy logic control approach with computational machine learning. In: 2023 11th international conference on control, mechatronics and automation (ICCMA); IEEE; 2023. p. 346–51.
[103] Ahmad I, M'Zoughi F, Aboutalebi P, Garrido I, Garrido AJ. Fuzzy logic control of an artificial neural network-based floating offshore wind turbine model integrated with four oscillating water columns. Ocean Eng 2023;269:113578.
[104] Ahmad I, M'Zoughi F, Aboutalebi P, Garrido I, Garrido AJ. A regressive machine-learning approach to the non-linear complex FAST model for hybrid floating offshore wind turbines with integrated oscillating water columns. Sci Rep 2023;13(1):1499.
[105] Aboutalebi P, M'Zoughi F, Garrido I, Garrido AJ. A control technique for hybrid floating offshore wind turbines using oscillating water columns for generated power fluctuation reduction. J Comput Des Eng 2023;10(1):250–65.
[106] Aboutalebi P, M'Zoughi F, Martija I, Garrido I, Garrido AJ. Switching control strategy for oscillating water columns based on response amplitude operators for floating offshore wind turbines stabilization. Appl Sci 2021;11(11):5249.
[107] Aboutalebi P, M'Zoughi F, Ahmad I, Garrido AJ, Garrido I. A control approach on hybrid floating offshore wind turbines for platform and generated power oscillations reduction at below-rated wind speed. In: International workshop on soft computing models in industrial and environmental applications; Springer; 2022. p. 505–14.
[108] Fenu B, Bonfanti M, Mattiazzo G. Numerical investigation of a new hybrid floating wind turbine concept. In: Proceedings of the European wave and tidal energy conference, vol. 15; 2023.
[109] Zhu H, Hu C, Yoshida S. Modelling of a floating-type hybrid wind-wave system with oscillating water column wave energy converters: a study towards floater motion reduction. J Phys Conf Ser 2024;2767(7):072015.
[110] Sirigu M, Faraggiana E, Ghigo A, Bracco G. Development of MOST, a fast simulation model for optimisation of floating offshore wind turbines in simscape multibody. J Phys Conf Ser 2022;2257(1):012003. IOP Publishing.
[111] Si Y, Chen Z, Zeng W, Sun J, Zhang D, Ma X, et al. The influence of power-take-off control on the dynamic response and power output of combined semi-submersible floating wind turbine and point-absorber wave energy converters. Ocean Eng 2021;227:108835.
[112] Zhang K, Chen M, Zhou H, Chen N, Liang C, Hallak TS, et al. An efficient time domain model for hybrid floating wind-wave platforms considering multi-body constraints and mooring system. Ocean Eng 2025;334:121601.
[113] Faraggiana E, Sirigu M, Ghigo A, Petracca E, Mattiazzo G, Bracco G. Conceptual design and optimisation of a novel hybrid device for capturing offshore wind and wave energy. J Ocean Eng Mar Energy 2024;10(1):35–56.
[114] Burton T, Jenkins N, Sharpe D, Bossanyi E. Wind energy handbook. John Wiley & Sons; 2011.
[115] Manwell JF, McGowan JG, Rogers AL. Wind energy explained: theory, design and application. John Wiley & Sons; 2010.
[116] Ning SA. A simple solution method for the blade element momentum equations with guaranteed convergence. Wind Energy 2014;17(9):1327–45.
[117] Mitra A, Sarkar S, Chakraborty A, Das S. Sway vibration control of floating horizontal axis wind turbine by modified spar-torus combination. Ocean Eng 2021;219:108232.
[118] Fenu B, Attanasio V, Casalone P, Novo R, Cervelli G, Bonfanti M, et al. Analysis of a gyroscopic-stabilized floating offshore hybrid wind-wave platform. J Mar Sci Eng 2020;8(6):439.
[119] Bianchi FD, Mantz RJ, De Battista H. Wind turbine control systems. Principles, modelling and gain scheduling design. London: Springer; 2006.
[120] Neshat M, Sergiienko NY, Nezhad MM, da Silva LSP, Amini E, Marsooli R, et al. Enhancing the performance of hybrid wave-wind energy systems through a fast and adaptive chaotic multi-objective swarm optimisation method. Appl Energy 2024;362:122955.
[121] Zhao H, Stansby P, Liao Z, Li G. Optimal control of a hybrid offshore platform combining a wind turbine and multiple floats. In: 2024 IEEE international conference on industrial technology (ICIT). IEEE; 2024. p. 1–6.
[122] Zhu H. Optimal semi-active control for a hybrid wind-wave energy system on motion reduction. IEEE Trans Sustain Energy 2022;14(1):75–82.
[123] Reyes V, Rodríguez JJ, Carranza O, Ortega R. Review of mathematical models of both the power coefficient and the torque coefficient in wind turbines. In: 2015 IEEE 24th international symposium on industrial electronics (ISIE); IEEE; 2015. p. 1458–63.
[124] Castillo OC, Andrade VR, Rivas JJR, González RO. Comparison of power coefficients in wind turbines considering the tip speed ratio and blade pitch angle. Energies 2023;16(6):2774.
[125] Zhu H, Hu C. A study on control of wave energy converter for motion suppression of semisubmersible. IFAC-PapersOnLine 2016;49(23):380–85.
[126] Francis BA, Wonham WM. The internal model principle of control theory. Automatica 1976;12(5):457–65.
[127] M'Zoughi F, Aboutalebi P, Garrido I, Garrido AJ, De La Sen M. Complementary airflow control of oscillating water columns for floating offshore wind turbine stabilization. Mathematics 2021;9(12):1364.
[128] M'Zoughi F, Garrido I, Garrido AJ, De La Sen M, et al. Fuzzy airflow-based active structural control of integrated oscillating water columns for the enhancement of floating offshore wind turbine stabilization. Int J Energy Res 2023;2023.
[129] Papillon L, Costello R, Ringwood JV. Boundary element and integral methods in potential flow theory: a review with a focus on wave energy applications. J Ocean Eng Mar Energy 2020;6(3):303–37.
[130] Pérez T, Fossen T. Time-vs. frequency-domain identification of parametric radiation force models for marine structures at zero speed. Model Identif Control 2008;29(1):1–19.
[131] Liu Y, Iwashita H, Hu C. A calculation method for finite depth free-surface green function. Int J Nav Archit Ocean Eng 2015;7(2):375–89.
[132] Ljung L. System identification. In: Signal analysis and prediction. Springer; 1998. p. 163–73.
[133] Perez T, Fossen TI. A matlab toolbox for parametric identification of radiation-force models of ships and offshore structures; 2009.
[134] Zhu H, Hu C, Liu Y. Optimum design of a passive suspension system of a semisubmersible for pitching reduction. J Dyn Syst Meas Control 2016;138(12):121003.
[135] Faedo N, Celesti ML. On the role of modelling uncertainty in optimal control and performance assessment of wave energy conversion systems. In: ISOPE international ocean and polar engineering conference; ISOPE; 2024, pp. ISOPE–I.

[136] López-Queija J, Robles E, Llorente JI, Touzon I, López-Mendia J. A simplified modeling approach of floating offshore wind turbines for dynamic simulations. Energies 2022;15(6):2228.
[137] McCoy A, Musial W, Hammond R, Mulas Hernando D, Duffy P, Beiter P, et al. Offshore wind market report: 2024 edition. Tech. Rep. Golden, CO, United States: National Renewable Energy Laboratory (NREL); 2024.
[138] Ma K-T, Luo Y, Kwan C-T-T, Wu Y. Mooring system engineering for offshore structures. Gulf Professional Publishing; 2019.
[139] Masciola M. Map+ + documentation. Golden, CO, USA: NREL; 2018.
[140] Davidson J, Ringwood JV. Mathematical modelling of mooring systems for wave energy converters—a review. Energies 2017;10(5):666.
[141] Celesti ML, Paduano B, Peña-Sanchez Y, Pasta E, Faedo N, Ringwood JV. On the behaviour of a combined wind-wave energy conversion platform under energy-maximising control conditions. In: OCEANS 2023-Limerick; IEEE; 2023. p. 1–6.
[142] Celesti ML, Faedo N, Mattiazzo G. Stabilisation and energy absorption control for wind-wave hybrid platforms: a generalised lqr approach. In: ISOPE international ocean and polar engineering conference. ISOPE; 2024, p. ISOPE–I.
[143] Stockhouse D, Phadnis M, Henry A, Abbas NJ, Sinner M, Pusch M, et al. A tutorial on the control of floating offshore wind turbines: stability challenges and opportunities for power capture. IEEE Control Syst 2024;44(5):28–57.
[144] Ringwood JV, Bacelli G, Fusco F. Energy-maximizing control of wave-energy converters: the development of control system technology to optimize their operation. IEEE Control Syst Mag 2014;34(5):30–55.
[145] Shahroozi Z. Survivability control using data-driven approaches and reliability analysis for wave energy converters [Ph.D. dissertation]. Acta Universitatis Upsaliensis; 2024.
[146] Liberzon D. Calculus of variations and optimal control theory: a concise introduction. Princeton University Press; 2011.
[147] Marler RT, Arora JS. The weighted sum method for multi-objective optimization: new insights. Struct Multidiscip Optim 2010;41:853–62.
[148] Deb K, Pratap A, Agarwal S, Meyarivan TAMT. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans Evol Comput 2002;6(2):182–97.
[149] Faedo N, Olaya S, Ringwood JV. Optimal control, MPC and MPC-like algorithms for wave energy systems: an overview. IFAC J Syst Control 2017;1:37–56.
[150] Nazaré T, Gadelha J, Nepomuceno E. Enhancing real-world inverted pendulum stabilization: addressing external perturbations with feedback and model predictive control. In: 2023 21st IEEE interregional NEWCAS conference (NEWCAS). IEEE; 2023. p. 1–2.
[151] Bay J. Fundamentals of linear state space systems; 1999.
[152] Torrisi FD, Bemporad A. HYSDEL-a tool for generating computational hybrid models for analysis and synthesis problems. IEEE Trans Control Syst Technol 2004;12(2):235–49.
[153] Peña-Sanchez Y, Windt C, Davidson J, Ringwood JV. A critical comparison of excitation force estimators for wave-energy devices. IEEE Trans Control Syst Technol 2019;28(6):2263–75.
[154] Zhan S, Li G. Linear optimal noncausal control of wave energy converters. IEEE Trans Control Syst Technol 2018;27(4):1526–36.
[155] Pena-Sanchez Y, Mérigaud A, Ringwood JV. Short-term forecasting of sea surface elevation for wave energy applications: the autoregressive model revisited. IEEE J Ocean Eng 2018;45(2):462–71.
[156] Zhu H, Hu C, Sueyoshi M, Yoshida S. Integration of a semisubmersible floating wind turbine and wave energy converters: an experimental study on motion reduction. J Mar Sci Technol 2020;25:667–74.
[157] Bracco G, Giorcelli E, Mattiazzo G. ISWEC: a gyroscopic mechanism for wave power exploitation. Mech Mach Theory 2011;46(10):1411–24.
[158] Hansen RH. Design and control of the power take-off system for a wave energy converter with multiple absorbers [Ph.D. dissertation]. Aalborg, Denmark: Aalborg University; 2013.
[159] Antoulas AC, Sorensen DC. Approximation of large-scale dynamical systems: an overview. Int J Appl Math Comput Sci 2001;11(5):1093–121.
[160] Pasta E, Faedo N, Mattiazzo G, Ringwood JV. Towards data-driven and data-based control of wave energy systems: classification, overview, and critical assessment. Renew Sustain Energy Rev 2023;188:113877.
[161] Shi W, Fu J, Ren Z, Jiang Z, Wang T, Cui L, et al. Real-time hybrid model tests of floating offshore wind turbines: status, challenges, and future trends. Appl Ocean Res 2023;141:103796.
[162] Garcia-Sanz M. Control co-design: an engineering game changer. Adv Control Appl Eng Ind Syst 2019;1(1):e18.
[163] Celesti ML, Paduano B, Peña-Sanchez Y, Pasta E, Faedo N, Ringwood J. Design considerations for a hybrid wind-wave platform under energy-maximising control. In: Proceedings of the European wave and tidal energy conference, vol. 15; 2023.
[164] Hu J, Zhou B, Vogel C, Liu P, Willden R, Sun K, et al. Optimal design and performance analysis of a hybrid system combing a floating wind platform and wave energy converters. Appl Energy 2020;269:114998.
[165] Pao LY, Pusch M, Zalkind DS. Control co-design of wind turbines. Annu Rev Control Robotics Auton Syst 2024;7.
[166] Da Silva JG, Nazaré T, Costa M, Lacerda MJ, Nepomuceno E. Engineering and technology applications of control co-design: a survey. IEEE Access 2024;12:81692–717.