# Optimal control and control-oriented modelling of wave energy conversion systems

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**Abstract**

The pathway towards efficient exploitation of the vast energy available in ocean waves is inherently linked to suitable control technology. In particular, effective commercialisation of wave energy conversion systems (WECs) strongly depends upon the availability of tailored controllers able to maximise energy extraction from the wave resource, while minimising risk of component damage. The control problem for WEC systems naturally lends itself towards optimal control theory, where the control objective is, effectively, optimal energy capture, subject to a set of device-dependent physical limitations. Not only such a control objective can often lead to non-convex solution spaces, but achieving optimality depends upon future knowledge of external uncontrollable inputs, which renders this problem inherently non-causal, further departing from traditional tracking/regulation objectives. This open invited track intends to gather novel state-of-the-art strategies from the field of system dynamics and control, providing innovative and efficient solutions to the WEC control problem, with the potential to greatly contribute in the path towards enabling effective exploitation of the vast wave energy resource available.

# 1 Motivation and relevance

Following the sharp increase in the price of traditional fossil fuels, in combination with issues of security of supply, and pressure to honor greenhouse gas emission limits, much attention has turned to renewable energy sources in recent years. **Ocean wave energy** is a massive and untapped resource, which can make a valuable contribution towards a sustainable, global, energy mix: the wave energy resource has been estimated (worldwide) to be around $3.7$ [TW] and about $32000$ [TWh/yr] in [7] and [3], which would cover $\approx 20\%$ of the current global energy consumption (see Figure 1 for a detail on the distribution of the wave energy source worldwide). Despite the fact that ocean waves constitute a vast resource, **wave energy converters** (WECs) have yet to make significant progress towards commercialisation. The main reason for the lack of proliferation of wave energy can be attributed to the fact that harnessing the irregular reciprocating motion of the sea is not as straightforward as, for example, extracting energy from the wind. This is clearly reflected in the striking absence of clear technology convergence, with over a *thousand* different concepts and patents proposed over the years [2, 8, 1]. One stepping stone to achieve the commercialisation objective is the availability of appropriate **control technology**, such that *energy conversion is performed as economically as possible*, minimising the delivered energy cost, while also maintaining the structural integrity of the device, minimising wear on WEC components, and operating across a wide range of sea conditions [9, 6].

Though energy-maximising controllers can effectively maximise energy extraction from ocean waves, the control problem itself does not fit into a 'traditional' form, *i.e.* tracking/regulation. As a matter of fact, the control problem for WECs naturally lends itself towards *optimal control theory*, where the control objective is, effectively, optimal energy capture, subject to a set of device-dependent physical limitations (translated as state and input constraints). Not only such a control objective can often lead to non-convex solution spaces, but achieving 'true' optimality depends upon future knowledge of external uncontrollable inputs (*i.e.* forces exerted on the device as a consequence of the incoming wave field), which renders this problem inherently non-causal, further departing from traditional tracking/regulation objectives (see *e.g.* [5] for further detail).

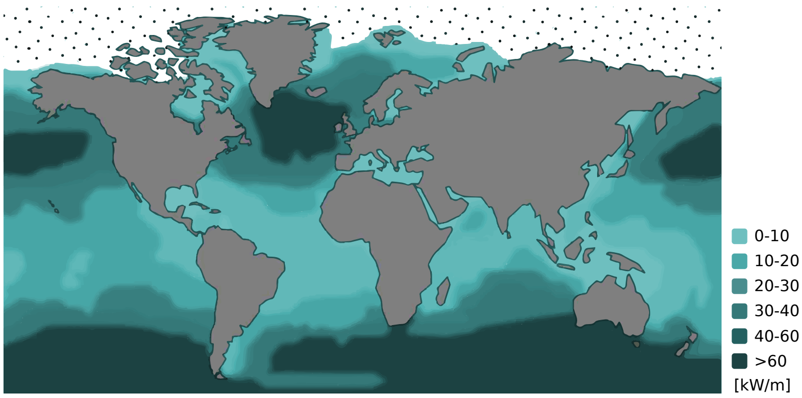


Figure 1: Average annual wave energy transport [kW/m]. Image adapted from [4].

As such, suitable energy-maximising control technology for wave energy systems virtually always depends upon the availability of three fundamental 'building blocks', briefly described in the following: **(1)** A parsimonious **control-oriented dynamical model**, describing the motion of the WEC, obtained by means of physical principles/available system data and the subsequent application of model reduction/system identification techniques; **(2)** a **model-based optimal control framework**, able to efficiently compute the corresponding energy-maximising control law, subject to a set of constraints, defined according to the physical limitations of the device; and **(3)** a combination of **unknown-input estimation and forecasting techniques**, to provide instantaneous and future values of the (generally non-measurable) wave excitation force.

Motivated by the fundamental requirements of control for wave energy systems, and the strong necessity of novel techniques to approach the WEC control problem, this open invited track intends to gather novel state-of-the-art strategies from the field of system dynamics and control, providing innovative and efficient solutions to components **(1)**, **(2)**, and **(3)** of the WEC energy-maximising optimal control problem. The proposed open track will also encourage exchange of ideas regarding data-driven technology, with emphasis on Koopman-theory-based approaches towards efficient control-oriented modelling and optimal control for wave energy control systems. Model-free control strategies, capable of effectively handling the specifications of the WEC control problem (including appropriate constraint handling), will also be welcomed. Such novel control technology, capable of achieving optimal energy-capture with real-time performance, is of fundamental importance towards achieving commercialisation of wave energy systems, hence directly enabling effective exploitation of the wave resource in the near future.

The open track proposers have successfully organised a series of invited sessions on wave energy control systems in the past, within relevant systems and control conferences including, *e.g.* the American Control Conference (ACC), IFAC Conference in Conference on Control Applications in Marine Systems, Robotics and Vehicles (IFAC CAMS), and 2014, 2017 and 2020 IFAC World Congress. These invited sessions have been always well attended, with a good geographical balance and high quality contributions.

## References


[1] Joao Cruz. *Ocean wave energy: current status and future perspectives*. Springer Science & Business Media, 2008.

[2] Benjamin Drew, Andrew R Plummer, and M Necip Sahinkaya. A review of wave energy converter technology, 2009.

[3] Ottmar Edenhofer, Ramón Pichs-Madruga, Youba Sokona, Kristin Seyboth, Susanne Kadner, Timm Zwickel, Patrick Eickemeier, Gerrit Hansen, Steffen Schlömer, Christoph von Stechow, et al. *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change*. Cambridge University Press, 2011.

[4] Nicolás Faedo. *Optimal control and model reduction for wave energy systems: A moment-based approach*. PhD thesis, Department of Electronic Engineering, Maynooth University, 2020.

[5] Nicolás Faedo, Giordano Scarciotti, Alessandro Astolfi, and John V Ringwood. Nonlinear energy-maximizing optimal control of wave energy systems: A moment-based approach. *IEEE Transactions on Control Systems Technology*, 29(6):2533–2547, 2021.

[6] Umesh A Korde and John V. Ringwood. *Hydrodynamic control of wave energy devices*. Cambridge University Press, 2016.

[7] Gunnar Mork, Stephen Barstow, Alina Kabuth, and M Teresa Pontes. Assessing the global wave energy potential. In *ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering*, pages 447–454. American Society of Mechanical Engineers, 2010.

[8] Arthur Pecher and Jens Peter Kofoed. *Handbook of ocean wave energy*. Springer London, 2017.

[9] John V Ringwood, Giorgio Bacelli, and Francesco Fusco. Energy-maximizing control of wave-energy converters: The development of control system technology to optimize their operation. *IEEE Control Systems*, 34(5):30–55, 2014.