Digital Twin Models for Marine Offshore Renewable

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Wave Energy is emerging as a promising renewable energy source. Its attractiveness stems not only from its vast potential but also from its suitability for areas with scarce land for energy production. However, Wave Energy remains substantially untapped due to several challenges that still need to be overcome. One of these challenges regards the inherent stochastic and intermittent behaviour of ocean waves, which represents a significant challenge for the grid integration of these Renewable Energy Sources (RES). On the other hand, the Levelised Cost of Energy (LCoE) for current Wave Energy Converters (WECs) still exceeds that of other more mature RES, such as wind and solar.

This thesis addresses these challenges by developing the fundamental building blocks of a Digital Twin (DT) framework for WECs, based on Internet of Things (IoT) infrastructure and advanced Machine Learning (ML) methodologies. These building blocks of the DT correspond to the three main research pillars of this thesis. First, I presented a WEC power forecasting methodology that can act as the *Digital Shadow* of the device and enables its grid integration. The methodology enables the prediction of the power delivered to the grid of WEC devices over horizons from 1min to 240min. To this end, I designed and optimised various state-of-the-art ML algorithms with different forecasting horizons for performing point predictions of the power delivered to the grid of WECs. Depending on the forecasting horizon, these predictions can be useful for various applications, such as WEC control, State-Estimation and Demand/Response. Furthermore, I analysed the impact of the downsampling technique by aggregating the raw data sampled at 0.1s into time steps ranging from 1s to 15min. Additionally, I implemented Prediction Intervals to compute the inherent uncertainties associated with the point forecasts. Moreover, I investigated the effectiveness of exogenous inputs in forecasting the WEC's power delivered to the grid.

Secondly, to bridge the LCoE gap with other renewables and enhance the economic viability of WECs, I developed an ML-based surrogate model, that can act as the *Digital Model* and accelerate WEC performance evaluation. The surrogate model receives the parameters describing single WEC setups as input and outputs the device's general site-independent power matrix. The surrogate comprises two main

components: a classification and a regression algorithm. The classification algorithm evaluates the feasibility of the given parameter set, while the regression accurately predicts the device's power matrix. I evaluated and compared the performance of various state-of-the-art ML algorithms for the classification and regression tasks.

Finally, I designed and developed a distributed Internet of Things Software platform that enables the collection, storage, and management of heterogeneous data streams in a Multi-Energy Systems scenario, and that provides the middleware backbone required to integrate the two data-driven components above. The platform follows the microservices design pattern and enables extending its functionalities in a plug-and-play fashion. I validated the platform across three use cases: Indoor Environmental Quality monitoring and automatic component control; WEC power monitoring and forecasting; and monitoring a fleet of Atmospheric Water Generators. Furthermore, I performed communication tests to evaluate the transmission performance, demonstrating that latencies are within acceptable limits for the applications studied.

Overall, this thesis delivers the building blocks and the architectural foundation of a DT for WECs.