Wave Energy Model

In order to define the most suitable wave energy converter for the North Carolina, we investigated a few models such as RM3 from SANDIA [1], Oyster from Aquamarine Power Ltd [2], Wavebob [3], and Pelamis [4]. The Pelamis wave energy converter is a 750 KW attenuator type model, which has been extensively used in the literature for the assessment of wave energy resources [5] [6]. A scaled version of this model was produced by the University of Edinburgh [7] at rated capacity of 1.5 MW and presented the best compatibility with the characteristics of North Carolina in terms of CF and cost. Therefore, this will be the model used in the further analysis of this work.

Based on [7], the limits for deployment depth were set to 50-150m, and the packing density was considered as 12.5 devices/km^2. Unfortunately, in the literature, no cost estimates were carried out for this scaled Pelamis model; thus, our cost structure is based on information from the 750KW model and other estimates carried out by SANDIA regarding its ocean-based technologies.

1. Cost Breakdown

The cost structure described in this section is based on a 150MW deployment, one hundred wave energy converters of 1.5 MW each. This is a large deployment for an emerging technology, but since the propose of this work is to evaluate the integration of ocean energy technologies between themselves and the possibly with other electrical system it is important to have a cost estimate that represents a commercial-scale project so we can more fairly compare their LCOE costs.

For the wave energy technology, it was considered a project economic life of 20 years and a fixed charge rate (FCR) of 11.3% as done in [1] for the reference model 3.

In the cost considerations presented next, it was used two main references [1], and [8]. The reference [1] presents a very detailed cost structure for a 286 KW wave converter (point absorber). Despite the differences between this model and the Pelamis model, it is possible to use several of the cost assumptions presented in [1] and extrapolate them for our analysis as it will be explained in each of the next sections. On the other hand, the reference [8] presents one of the most detailed cost structures for the Pelamis model, but it lacks several details, making it difficult to assess the influence of site-specific characteristics (e.g., distance from shore) in the total project cost. This limitation will be mitigated partially with information from [1].

1.1. Transmission system

Based on the previous analysis carried out for the ocean current technology, a transmission line of 132 kV with a 3-core XLPE cable of 500mm^2 can safely serve a 150MW deployment (Table I).

Using equations (6-10 and 15) with $N_c = 1$, $cc_{AC} = 0.631$ M\$/km, $\ell_{TC} = 1.2D_{SL}$, and $S_{TL} = 150MVA$, we can estimate the capital expenditures related to the transmission system as (59), and the operational expenditures as (60).

CAPEX
$$CAPEX_{AC}^{TL} = 16.38 + 0.98\, D_{SL} [\mathrm{M\$}] \tag{59}$$

OPEX $$OPEX_{AC}^{TL} = 0.025 \cdot CAPEX_{AC}^{TL} \text{ [M\$/Year]} \quad (60)$$

1.2. CAPEX- Development

As already explained, the development cost includes permitting and environmental compliance, site assessment and project design, engineering, and management.

The costs related to environmental compliance and site assessment are strongly dependent on the size of the area investigated and will be considered as the values reported by [1] for 100 units. This is a conservative estimation given that the packing density of the model used by [1] is significantly lower than the values reported for the Pelamis model.

Similar to [1] the costs related to project design, engineering, and management are assumed to be 1% of the hard cost of the device.

Development Cost: $$CDev = 7.3 + 0.01 \cdot (CInf + CMF + CSC + CPTO + CIPM + CInst) \text{ [M\$]} \quad (61)$$

1.3. CAPEX- Infrastructure

As already mentioned, the infrastructure costs include the subsea cables (34kV), terminations and connectors, and O&M vessels.

Following the assumptions of [1], the cost of terminations and connections is going to be assumed as 10% of the cable cost and the O&M vessel cost is scaled from [1] based on the total installed capacity.

For the 34kV electrical system, we decided for the use of a 95mm^2 three core copper conductor from ABB [9]. At 34kV, this cable has a capacity of 18MVA, being able to connect at a maximum of twelve 1.5MVA turbines to the offshore substation where the energy is finally transmitted to the shore. The cost for this cable was estimated in 136 [$/m] based on equation (62).

Finally, the infrastructure cost can be determined by (62).

Infrastructure Cost: $$CInf = 0.1496\, \ell_{34kV} + 7.74 \cdot \left(\frac{1500}{286}\right) \text{ [M\$]} \quad (61)$$

Infrastructure Cost: $$CInf = 0.1496\, \ell_{34kV} + 40.59 \text{ [M\$]} \quad (62)$$

1.4. CAPEX- Mooring/Foundation

Based on [8], the mooring costs for the 750 kW Pelamis model can be estimated at USD 0.4 million per device. In order to be conservative, we will assume that this cost will double for the 1.5 MW model (USD 0.8 million).

Mooring & Foundation: $$CMF = 0.8 \cdot 100 = 80 \text{ [M\$]} \quad (63)$$

1.5. CAPEX- Structural Components and Power Takeoff

Based on [8], these costs can be estimated at USD 4 million per device (750 kW). Again, to be conservative, we will assume that the costs for the 1.5MW model would double from the values reported by [8].

Structural Components & PTO Costs: $$CSC + CPTO = 8 \cdot 100\ [\text{M\$}] = 800\ [\text{M\$}] \tag{64}$$

1.6. CAPEX- Subsystem Integration & Profit Margin

As in [1], we considered the costs of subsystem integration (e.g., grid connection) and profit margin as 10% of the power take-off and structural components.

Subsystem Integration & Profit Margin $$CIPM = 0.1 \cdot 800 = 80[\text{M\$}] \tag{65}$$

1.7. CAPEX- Installation

The installation costs include transport of equipment to the staging site, mooring installation, offshore cable installation (34kV cable), device installation, and commissioning. As we could notice from the results presented for the ocean current technology, for a fixed number of turbines, most os the installation costs can be described by a fixed charge. This condition becomes even more expressive for the wave energy technologies where the deployments are closer to the shore.

Finally, given the lack of detailed information regarding deployments for the Pelamis model, the installation costs will be estimated as a percentage of the total CAPEX costs, based on the results of the RM3 model from SANDIA [1]. On equation (66), we exclude the CAPEX related to the transmission system since the installation costs are already computed for this case.

Installation: $$CInst = (CAPEX - CAPEX_{AC}^{TL}) \cdot 0.097\ [\text{M\$}] \tag{66}$$

1.8. Contingency

The contingency cost is considered as 10% of the infrastructure, mooring, structural components, power take-off, integration & profit margin, and installation costs.

Contingency Cost: $$CCont = 0.1(CInf + CMF + CSC + CPTO + CIPM + CInst\ )\ [\text{M\$}] \tag{67}$$

1.9. Total CAPEX

Wave Energy: $$CAPEX = CAPEX_{AC}^{TL} + CDev + CInf + CMF + CSC + CPTO + CIPM + CInst + CCont[\text{M\$}] \tag{68}$$

Wave Energy: $$CAPEX = 1269.6 + 1.003\ D_{SL} + \ 0.186\ \ell_{34kV}\ [\text{M\$}] \tag{69}$$

1.10. OPEX

Based on the cost breakdown structure presented by SANDIA [1], for a fixed number of energy conversion devices, the majority of the OPEX costs are fixed, this was also the results we found for the ocean current technology.

This way, the OPEX cost estimated for our wave energy deployments are defined as a percentage of the total CAPEX cost according to the results presented by [1] for the reference model 3.

Wave Energy OPEX: $$OPEX = (CAPEX - CAPEX_{AC}^{TL}) \cdot 2.4\% + OPEX_{AC}^{TL} [\text{M\$}] \quad (71)$$

Wave Energy OPEX: $$OPEX = 30.4868 + 0.025 \cdot D_{SL} + 4.5 \cdot 10^{-3} \cdot \ell_{34kV} \quad (72)$$

References

[1] V. S. Neary, M. Previsic, R. A. Jepsen, M. J. Lawson, Y. H. Yu, A. E. Copping, A. A. Fontaine, K. C. Hallett and D. K. Murray, "Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies," Sandia National Laboratories, 2014.

[2] L. Cameron, R. Doherty, A. Henry, K. Doherty, J. V. ’. Hoff, D. Kaye, D. Naylor, S. Bourdier and T. Whittaker, "Design of the Next Generation of the Oyster Wave Energy Converter," in *3rd International Conference on Ocean Energy*, 2010.

[3] J. B. Frandsen, M. Doblaré and P. Rodríguez-Cortés, "Preliminary technical assessment of the Wavebob energy converter concet," Abengoa Seapower, 2012.

[4] J. B. Frandsen, M. Doblaré and P. Rodríguez-Cortés, "Technical assessment of the Pelamis Wave Energy Converter concept," Abengoa Seapower, 2012.

[5] N. Guillou and G. Chapalain, "Annual and seasonal variabilities in the performance of wave energy converters," *Energy,* vol. 165, pp. 812-823, 2018.

[6] C.-K. Kim, J. E. Toft, M. Papenfus, G. Verutes, A. D. Guerry, M. H. Ruckelshaus, K. K. Arkema, G. Guannel, S. A. Wood, J. R. Bernhardt, H. Tallis, M. L. Plummer, B. S. Halpern, M. L. Pinsky, M. W. Beck and F. Ch, "Catching the Right Wave: Evaluating Wave Energy Resources and Potential Compatibility with Existing Marine and Coastal Uses," *PLOS ONE,* vol. 7, no. 11, 2012.

[7] University of Edinburgh, "Matching Renewable Electricity Generation With Demand," University of Edinburgh, 2006.

[8] C. Bosserelle, S. Reddy and J. Krüger, "Wave and Coasts in the Pacific: Cost analysis of wave energy in the Pacific," Pacific Community, 2015.

[9] ABB, "XLPE Submarine Cable Systems Attachment to XLPE Land Cable Systems - User´s Guide," ABB, 2019.

[10] A. J. Collin, A. J. Nambiar, D. Bould, B. Whitby, M. A. Moonem, B. Schenkman, S. Atcitty, P. Chainho and A. E. Kiprakis, "Electrical Components for Marine Renewable Energy Arrays: A Techno-Economic Review," *Energies,* vol. 10, 2017.

[11] P. Djapic and G. Strbac, "Cost Benefit Methodology for Optimal Design of Offshore Transmission Systems," Centre for Sustainable Electricity & Distribution Generation, 2008.

[12] X. Xiang, M. M. C. Merlin and T. C. Green, "Cost analysis and comparison of HVAC, LFAC and HVDC for offshore wind power connection," in *12th IET International Conference on AC and DC Power Transmission (ACDC 2016)*, 2016.