Techno-economic evaluation of sand pumping system powered by a wave energy farm

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***Abstract*— As the world is transitioning away from fossil fuels and towards intermittent and unpredictable renewable energies, there is a growing need to integrate intensive energy usage technologies with renewable energy sources. This study presents a techno-economic evaluation of a wave-energy converter and fixed sand transportation system in Figueira da Foz, Portugal. The study aims to address the dual challenges of technically providing the required energy to transport the sand accumulated in the northern part of the river and the economic benefit of this solution for the municipality. The research involved a comprehensive analysis of wave technologies, sand transportation systems, and economic models. The energy generation potential of Figueira da Foz's wave climate was assessed, along with the sand transportation needs of the region. The Levelized Cost of Energy (LCOE) of the wave plant was calculated, and electricity prices for selling or buying from the grid were defined. The Net Present Value (NPV) of the project was analysed, considering various interest rates, Feed-In Tariffs, and sand transportation prices. The results demonstrate the feasibility of the proposed system, offering insights into the integration of wave energy conversion with coastal management. The findings contribute to the broader understanding of renewable energy solutions and provide a foundation for future development in similar coastal regions.**

Keywords: Wave energy converter, Sand Transportation, Oscillating Water Column, Feed-In Tariff

I. INTRODUCTION

Throughout the years, several maritime accidents occurred at Figueira da Foz's port entrance caused by rough sea conditions which led the previous municipality to look for solutions to increase the safety conditions when at the port's entrance. The solution executed was extending the northern seawall of the port in 2011. Nowadays, more than a decade after the new structure was finished, millions of cubic meters of sand are deposited on the northern beach of the seawall (Praia da Claridade) and there is a lack of sand in the southern part of the town. The repetition of these events on a yearly base has started a public discussion on the topic to solve the sand transportation issue. The existence of this problem creates a need for solutions that can decrease sand deposition and consequential erosion of the coastal dunes as the one being currently adopted does not provide desirable results. Many solutions have been studied to solve this issue. The implementation of a fixed bottom pump system has been studied as well but one of the concerns with this solution is the energetic need evolved that can result in high operational and maintenance costs for the city. With the increasing energetic need that would result in running the pumping system, it is mandatory to reflect in the way to power that facility.

II. LITERATURE REVIEW

Sand transportation is a topic of which many hypotheses have been studied to measure the impact of new solutions. The current solution adopted by the municipality consists of a dredge sand system to decrease the consequences of natural sand deposition on the northern part of Figueira da Foz's port.

The erosion phenomenon is constantly happening along Portugal's coast by the action of the sea and river's activity. As a result of this erosion, sand and small bodies of rocks that can be either transported by wind or by water movement. This way, it is estimated that the current sand transportation profile on the coast along Figueira da Foz is mostly done in the north-to-south direction as in the majority of the country due to the activity of the Atlantic Ocean and predominant swell direction of Northwest [1]. It is estimated that the total transportation of sand is around 746 000 m^3 per year [1].

The current solutions for artificial sand transportation can be classified in: mobile systems (dredging); mixed systems (a junction of fixed solution with moving parts) and fixed systems.

Previous studies on the implementation of different sand transportation solutions applied to Figueira da Foz were studied and sized to a sand transportation capacity of 1 000 000 m^3. The costs and the Net Present Value associated with the implementation of different technologies for this location are depicted in Table I and II below [6].

TABLE 1
OPERATIONAL COSTS TAKEN FROM [6]

Operational costs		
Technology	**Exploitation Costs (M€)**	**Total costs (M€)**
Current Solution	30	30
Fixed System	43	72.2
Mixed System	59.6	86.3

TABLE 2
NET PRESENT VALUE TAKEN FROM [6]

Net Present Value		
Technology	**Transport volume (Mm^3)**	**NPV (M€)**
Current Solution	9	-64.8
Fixed System	35.8	274.2
Mixed System	33.5	263.8

Regarding the wave energy state of the art, the vast power potential of the oceans, wave motion alone holds the capability to generate an impressive 29,500 TWh of energy. wave energy generation complements wind energy, continuing to produce power even in the absence of wind. Optimal wave conditions for exploitation are identified in medium-high latitudes and deep waters (exceeding 40 m), where wave energy has been recorded to achieve power densities between 60-70 kW/m.

While 67% of current WEC concepts utilize floating mechanisms and a mere 19% employ fixed structures (IRENA, 2014), the predominant experience has been accumulated through: shoreline oscillating water columns, positioned on natural cliffs or breakwaters that are devices that; near-shore technologies, leveraging bottom-fixed solutions, often accompanied by terminal absorbers; offshore technologies, deployed at specific testing or pilot locations[8].

Europe continues to spearhead the market for wave energy technologies, yet other nations and regions are rapidly advancing. Historical milestones include the deployment of the 750 kW Pelamis prototype in the UK and the 2 MW Archimedes Wave Swing2 prototype in Portugal in 2004. Furthermore, in 2008, Portugal tested the first wave energy farm (2.25 MW) based on three Pelamis prototypes. Subsequent developments include Aquamarine Power's 315 kW and 800 kW Oysters, installed in the Orkney Islands in 2009 and 2011 respectively, and various projects by Dexawave in Denmark and Malta [8].

This way wave energy converters (WEC) can be classified in terms of the device location as onshore, offshore and shoreline. This system can use turbines driven by water, air, oil, or use wave energy to drive a mechanism (linear or rotational) and then transform this motion into electricity without an intermediate fluid. The device characterization can range from point absorber, in which the horizontal dimension is much smaller than the wavelength) or line absorber in case the capture system has a predominant dimension (length) which it can be either transverse or longitudinal to the incoming wave direction.

The classification based on the working principle can be: oscillating water column, oscillating body and overtopping.

In Figure 1 it can be seen an example of an oscillating water column device, the spar buoy that was the referenced wave energy converter chosen for this study [3].

Figure 1. Oscillating Water Column 1/10 model of a spar-buoy device.

Conversely, wave energy encounters barriers akin to those faced by the offshore wind and tidal energy sectors, such as: Environmental regulation and impact uncertainties; Investment needs: Given the current and forecasted costs, a market pull to attract private investment is imperative; Insufficient infrastructure: The absence and high costs of offshore grid connections and port facilities for Operations & Maintenance (O&M) are notable challenges; Planning and licensing procedures: Crucial to mitigating potential conflicts among various maritime users and minimizing potentially expensive administrative processes [3].

One of the strategies to decrease the price of energetic products is to rely on national or international entities in order to decrease their price. These subsidies can be pursued in order to achieve specific policy goals such as: providing affordable energy to low-income members of society; correcting prices caused by externalities; inducing technology learning and driving down its costs; enhancing energy security; and creating a new economy.

The Feed-In tariff is an energy subsidy type that consists of establishing a price to be paid to the producer by its electricity during a defined period of time. These costs are generally supported by the final consumers through an award on their electricity price depending on the technology type used, installation location and project dimension. This model enables the development of renewable energy in Europe and decreases uncertainty on possible return on the investment made by energy producers. The most successful Feed-In tariff usually includes: granted access to the grid; stable long-duration contracts (15 to 25 years); buying prices according to the production costs of the renewable energy technology.

To what concerns the wave energy technology Feed-In tariffs in Portugal, in 2010 it was granted a concession to the company Enondas, Energia das Ondas S.A. to commercially explore the energetic wave climate of a pilot zone. The remuneration regime depends on a ministerial decree subject to prior opinion from ERSE, a decree that has not yet been published, as the production regime has not yet reached commercial level. Secondly, when licensed, wave power devices would operate following one of three models (Figure 2): demonstration of concept (up to 4 MW of power per project and until 20MW of cumulative power installed), pre-commercial (up to 20 MW of power per project and until 100 MW of cumulative power installed) and commercial (above 100 MW of power per project), corresponding to each one a different Feed-In-Tariff (FIT) [4].

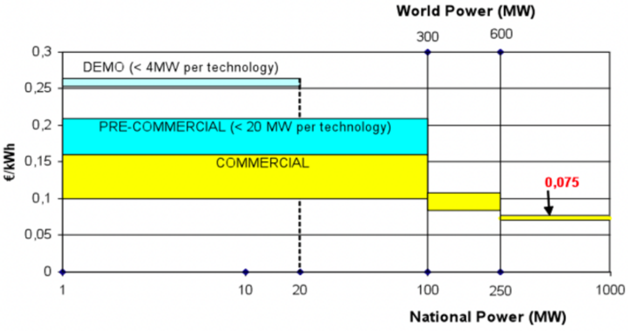


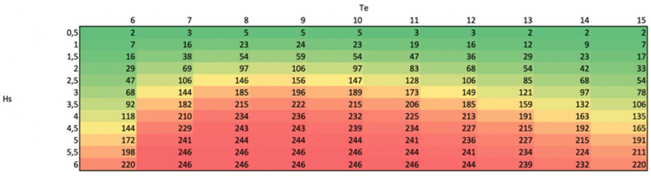
Figure 2. Wave Energy Feed-In Tariff in Portugal

It is important to mention the possible strategic benefits of a wave energy project that are not accountable using common economic indicators. For the Portuguese case, it would benefit from having another source of renewable energy that is not dependent on rain seasons, sun appearance or constant inland winds and make a slightly higher LCOE, like wave energy ones, viable.

III. SYSTEM'S DEFINITION

In this section, detailed calculations were used to find the energy need required to transport the sand accumulated in Figueira da Foz. The system chosen is a fixed bottom system, the typical working time will be 30 hours per week and it will require a transporting capacity of 640 m^3/hour to maintain an effective trench [5]. The system's configuration is: a piping system with a pressurized hydraulic circuit to discharge a water/sand mixture; two permanent exits being the first on the first sea wall of Cova-Gala and the second located south of the fifth Cova-Gala's seawall and temporary discharging points throughout Cabedelo and Cova-Gala's permanent exit points to allow the formation of a stable and reliable profile [6].

To what concerns the wave energy converter, the chosen device is an Oscillating Water Column spar buoy device. The considered device has a mean rated power of 260 kW. Figure 3 presents the device's power matrix and the corresponding power output for each wave energy climate.



					Te					
Hs	6	7	8	9	10	11	12	13	14	15
0,5	2	3	5	5	5	3	3	2	2	2
1	7	16	23	24	23	19	16	12	9	7
1,5	16	38	54	59	54	47	36	29	23	17
2	29	69	97	106	97	83	68	54	42	33
2,5	47	106	146	156	147	128	106	85	68	54
3	68	144	185	196	189	173	149	121	97	78
3,5	92	182	215	222	215	206	185	159	132	106
4	118	210	234	236	232	225	213	191	163	135
4,5	144	229	243	243	239	234	227	215	192	165
5	172	241	244	244	244	241	236	227	215	191
5,5	198	246	246	246	246	244	241	234	224	211
6	220	246	246	246	246	246	244	239	232	220

Figure 3. Wave energy converter power matrix.

The system was sized to match the energy demanded by the sand transportation system with the potential energy generation in Figueira da Foz. In order to find the energy demand profile, the current sand accumulated data is crossed with the energy need of the pumping system. The pumping system power consumption is 60 kW on baseload case and 1000 kW when pumping is being done [7]. The average electricity consumption by the sand transfer volume is 3.2 kW/m^3 due to local sand density of 1 630 kg/ m^3 [2].

The system will have energy management to prioritize the WEC energy production and consequently decrease external energy needs. This way, the main assumptions in system operation are: every time there is enough energy production in the wave energy converter farm for the transportation system operation, the electricity produced will be used by the transportation system; in case there is an excess of energy production by the wave farm compared to the energy demand, the excess energy is sold to the national grid; when there is no electricity production due to a lack of wave activity or by maintenance operation on the wave plant, the electricity will be bought to the national energy grid and there is no sand transportation; when the energy production is not enough to power the transportation process but is able to power the load consumption of the system, the system will consume the load electricity and the remaining will be sold to the national grid.

To determine the optimum number of wave energy converters in which the power production of the wave energy converter fully covers the energy required by the transportation system the following procedure is done. This procedure will be started by comparing the hourly wave farm output and the hourly load power needed to pump sand applying the system's energy constraints described before. After doing this management for every hour of the week it then obtains the new weekly sand accumulation profile obtained by the difference of the sand accumulation and the sum of all the hour transportation periods of that week. This process is then repeated for all the weeks of the considered period and we can have the system's total sand accumulated for a certain wave farm size. While the total sand accumulated volume is not transported by the transportation system, then there will be added a new wave energy converter and redefine the new values for the energy generation and sand transported as it will result in a new and higher hourly power output that consequently in more time periods when pumping operation is possible. The loop cycle will then stop when there is no sand accumulated at the end of whole period and the consequent full transportation of sand is possible. At the end of this stage, the power output, the sand transported, the number of wave energy converters, and the total energy exchanged with the grid are found. The loop cycle provided the information that a group of 10 converters is able to match the electrical power demand.

In order to define the economic aspects of the system, it needs to be defined the CAPEX and OPEX values to obtain the project's Levelized cost of Electricity and the revenues and costs of the project to obtain the Net Present Value.

The Capital Expenditures are the initial investments to build the whole system. This way, the initial costs considered are related to the procurement and installation of the devices. To calculate these costs an approach of cost per MW will be used and then calculated according to the total amount of power required to fulfill the energy demand of the transportation system.

The initial costs considered include contingencies, possible expenses that could appear in the construction or installation, about 7% of the material costs, and the decommissioning costs are considered to account for 50 000 €/MW which make the CAPEX of the WEC to be 5.2 M€. To what concerns the OPEX, these are the operational and maintenance costs associated with the system operation. The expenses incurred during the lifetime of the projects are divided into O&M costs, insurance, and sea bed lease rates. This is defined to be as 5% of the CAPEX per year subject to inflation (2%) [3].

It was defined that the project's revenues are: energy sales to the grid which is the wave energy converter generates electricity that is sold to the grid based on the Feed-In-Tariff (FIT) rate which provides a guaranteed price per MWh for the electricity produced by the wave energy converter; the fixed sand transportation system charges a fixed price per cubic meter of sand transported. Moreover, the project's expenses are: the cost to build and install the wave energy converter and the fixed sand transportation; the operational costs to run both systems (routine maintenance, repairs, and any other costs associated with the day-to-day operation of the system); electricity that is bought from the grid, which is also considered as an operational expense.

IV. TECHNICAL ANALYSIS DISCUSSION

The demand power of the sand transportation system requires a set of 10 wave energy converters, reaching a total power capacity of 2.6 MW. This power production together with energetic wave climate off Figueira da Foz's made it possible to reach an overall capacity factor of 0.35 for the defined time range. The annual energy production varies in the range of the 4.8-6.6 GWh depending on the wave climate on that year.

The results on the energy output show that, in a place with an energetic wave climate, the wave energy converter can be a reliable energy source as it could produce up to 3066 hours of rated power production per year. This number is still far from other renewable mature technologies but it still presents relevant results for a technology development scenario. The most frequent range of weekly energy output is the 50-150 MWh produced even though there is one week per year that the energy output is above 250 MWh.

The energy usage made by the transportation system itself, it accounts for almost 38% of the total power production after considering the energetic losses associated with the transportation of the electricity by the grid. The amount of electricity sold to the grid is in the range of 3.4 to 4 GWh per year. Once again, it is shown by the amount of energy exchanged that the system is oversized and it could be optimized to avoid overproduction of electricity.

The current system's management, considers the sand accumulation and wave climate from 2010 until 2021, resulting in a 4 million cubic meters of sand transportation surplus. These results show that at this rate it would need two cycles of the considered period, around 24 years, the total project's lifetime, for the system to retrieve the natural sand deposition it was made during the previous decade.

The fixed transportation solution still accumulates sand during periods of high transportation intensity but in the long term, it can compensate that effect. Furthermore, during periods in which the current solution shows low variation of sand accumulation, the fixed transportation system can transport sand at a rate of 40 000 m^3 of sand per week.

V. ECONOMIICAL ANALYSIS DISCUSSION

the scenario for a set of ten converters, summing a power capacity of 2.6 MW, gave a resulting LCOE range between 280 and 422 €/MWh depending on the discount rate of the project which is in the range of 5 to 15%. Table III below presents the different LCOE results depending on the discount rate presented.

TABLE 3
LCOE

Levelized Cost of Electricity witb discount rate	
Discount Rate (%)	**Levelized Cost of Electricity (€)**
5	280
7	306
9	334
10	349
15	422

In what concerns the Net Present Value of both solution combined, it shows different results depending on the Feed-In tariff of the project, the discount rate and the sand transport. Below in Tables IV and V there the different Net Present Value depending on the those variables.

TABLE 4
NET PRESENT VALUE WITH 9% DISCOUNT RATE

Net Present Value with 9% discount rate (M€)					
		Transport volume price (€/m^3)			
		3	4	5	6
Feed- In Tariff (€/MWh)	100	-21.0	-10.2	0.4	11.2
	150	-19.0	-8.2	2.4	13.2
	200	-17.0	-6.2	4.4	15.2
	250	-15.0	-4.2	6.4	17.2
	300	-12.9	-2.2	8.5	19.2
	350	-10.9	-0.2	10.5	21.2

TABLE 5
NET PRESENT VALUE WITH 12% DISCOUNT RATE

Net Present Value with 12% discount rate (M€)					
		Transport volume price (€/m^3)			
		3	4	5	6
Feed- In Tariff (€/MWh)	100	-24.0	-16.0	-7.3	1.3
	150	-22.0	-13.2	-4.5	4.1
	200	-19.2	-10.4	-1.8	6.9
	250	-16.4	-7.7	1.0	9.7
	300	-13.6	-4.9	3.8	12.5
	350	-10.8	-2.0	6.6	15.3

Even though, both variables impact positively the project, the increasing sand transportation price has a higher impact on the overall economic performance of the system. On the opposite side, a higher discount rate will result in higher updated operational and maintenance costs as well as an increased cost of capital. Finally, increasing the cost of sand transportation increases the revenue of the project but also makes this solution less attractive when compared with dredging and fixed sand transportation with alternative energy sources.

It is also important to highlight that adding to this NPV we should be adding the NPV that results from the implementation of a fixed sand transportation system and positively impacts the city. This way in all these scenarios we should add the lowest Net Present Value for the current solution in Figueira da Foz which corresponds to a 4% interest rate and is 114,62 M€. By adding both Net Present Values we obtain that even in the lowest economically performing scenario the system is economically viable.

VI. LIMITATIONS

Several limitations are still found in the study and should be addressed in future work.

Firstly there was a mislead of the wave energy constraints on very high energetic wave periods that are associated with storms and in most cases need to stop the system's energy production.

Secondly, it would be important to have a comparison of a fixed transportation facility powered by an alternative electricity producer (like offshore wind) or by the national grid in order to understand the competitiveness of this solution when compared to the already studied one. Moreover, it should be highlighted that the transported sand operation would be carbon-free and the cost of emissions should be added to the cost of the available solutions to fully understand the real competitiveness of this study.

VII. CONCLUSION

To conclude this study, the implementation of a fixed sand transportation powered by a wave energy converter should be considered as an alternative solution to the current sand transportation issues in Figueira da Foz.

In what concerns the technical feasibility of this study, the wave energy converter presents an above-average capacity factor of 35% which can be obtained by misleading the wave energy constraints on high energetic wave periods but also by the regular wave climate off the Figueira da Foz. Moreover, the direct relation between sand transport and active wave climate makes this solution effective as the need to transport a bigger sand volume occurs whenever there is enough wave energy to perform this sand movement. The system's dimension was oversized as during most of the time the majority of the energy is provided to the grid and around 35-40% to the fixed sand transportation solution.

From an economical point of view, by looking at this solution as a solo investment (combination of both systems), it presents different performances depending on the Feed-In tariff, interest rate, and cost of each cubic meter of sand transported. When comparing the current LCOE of the wave farm to other renewable's LCOE it can be seen that it is an expensive energy source due to being at a development stage but based on the technological forecasts that by 2030 the LCOE of wave energy can achieve values under 100 €/MWh this can totally change the economic result of the project. In case the Feed-In tariff is higher than the wave energy converter's LCOE and lower discount rates (7 or 9%), this can be a competitive solution when compared with the current dredging solution. When compared to the economic data available for a fixed transportation solution in Figueira da Foz there is a huge decrease in the energetic costs as there is no need for an external energy source. The solution described in this study has neglectable energy costs but on the other hand, has high O&M costs associated with the wave farm. It is also important to mention that due to the current Portuguese energy subsidies framework for wave energy, which can be a technology of great interest to Portugal, this can be a solution to solve a municipality issue, support the development of a technology, and guarantee the investment return to the investor.

Finally, we would like to highlight that from a municipality point of view, this project is economically viable for all the scenarios presented as the act of transporting all this sand would result in such a positive impact on the city, as well as on its surroundings, that it could compensate the negative Net Present Value obtained for higher interest rates and higher sand transportation prices of the project.

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