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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

AN EVALUATION OF WAVE ENERGY GENERATION AND COST OF ENERGY IN THE BLACK SEA

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ABSTRACT

The performance of several axisymmetric wave energy converters is studied by evaluating the yearly energy capture and the expense of energy in two sites in the Black Sea. The added mass, hydrodynamic damping, and wave forces exerted on the floats are calculated by a 3D panel method based on potential flow theory. The oscillations of the floats are calculated in the time domain by employing a family of Runge-Kutta Methods at various levels of accuracy and the yearly energy generated is calculated by taking into account the occurrence of sea states in a year. The expense of energy captured by each wave energy converter is evaluated by calculating the Levelized Cost of Energy. The results show that the WECs with Berkeley Wedge-Shaped floats generate the maximum amount of energy in Sinop and Hopa. The most economical wave energy converters are those with a cone float and with a Berkeley Wedge-Shaped float in Sinop and Hopa, respectively.

Keywords: *Wave Energy Generation, The Black Sea, Annual Energy Production, Cost Analysis*

KARADENİZ'DE DALGA ENERJİSİ ÜRETİMİ VE ENERJİ MALİYETİNİN DEĞERLENDİRİLMESİ

ÖZ

Eksenel simetrik dalga enerjisi dönüştürücülerinin Karadeniz'de iki bölgede gösterecekleri performans, yıllık enerji üretim miktarının ve enerjinin maliyetinin hesaplanmasıyla değerlendirilmiştir. Dalga enerjisi dönüştürücülerinin şamandıralarının ek su kütlesi, hidrodinamik sönüm katsayısı ve şamandıralara etki eden dalga kuvvetleri potansiyel akım teorisine dayalı 3 boyutlu bir panel yöntemi ile hesaplanmıştır. Şamandıraların yapmış olduğu salınım hareketlerinin hesabı ise farklı hassasiyet seviyelerindeki Runge-Kutta yöntemleri kullanılarak zamanın bağlısı olarak yapılmış ve yıllık enerji üretimi de bahse konu bölgelerde görülen deniz durumlarının bir yılda görülme süreleri ele alınarak yapılmıştır. Her bir dalga enerjisi dönüştürücüsü tarafından üretilen enerjinin birim maliyeti, sistemin ömrü boyunca karşılaşılacak tüm giderlerin maliyetinin göz önüne alınmasıyla hesaplanmıştır. Hesaplama sonuçları Berkeley Kama şeklindeki şamandıralara sahip dalga enerjisi dönüştürücülerinin Sinop ve Hopa'da en yüksek miktarda enerjiyi üretebileceklerini göstermektedir. Sinop ve Hopa'da en maliyet etkin dalga enerjisi dönüştürücüleri ise sırasıyla koni ve Berkeley Kama şeklinde şamandıralara sahip olan dalga enerjisi dönüştürücüleridir.

Anahtar Kelimeler: *Dalgalardan Enerji Üretimi, Karadeniz, Yıllık Enerji Üretimi, Maliyet Analizi*

1. INTRODUCTION

The necessity for generating energy for a long time without damaging the natural environment has led to the consideration of natural resources that were not adequately utilized before. The vast amount of energy contained by the waves on the surface of the oceans is a promising but challenging candidate. Many wave energy converter (WEC) designs have been proposed, some of them were even tested at sea under real conditions, but none of the devices have been successful in producing great amounts of energy economically. The efficiency of the wave energy converter arrays should be higher than that of the current level to add wave energy to the energy mix. Technological advancements in the design and control of the WECs allow them to produce energy more economically, which brings the WECs closer to commercial viability every day.

The expense of energy generation by an array of wave energy converters is a key factor for a project's economic competitiveness. Thus, the price of the unit energy must be evaluated during the design of WECs and necessary changes in the design should be applied to increase the power capture and to reduce the costs. The Levelized Cost of Energy (LCOE) is commonly considered the primary metric for assessing the economic performance of wave energy converters(Tetu & Chozas, 2021). Capital expenditures (CAPEX), operation and maintenance expenditures (OPEX), and decommissioning costs are the main elements of the total cost of an array of WECs considered in the early stages of design. The capital costs generally comprise the cost of the structure, the power take-off (PTO) system, moorings, installation, and project management. Different breakdowns of the CAPEX and OPEX are considered in various studies to calculate the costs and the LCOE of wave energy converter arrays. The cost of each element can be calculated by first estimating the cost of the material that the structure of the WEC will be manufactured and then utilizing the corresponding cost ratio of each element. The operation and maintenance costs which comprise planned and unplanned repairs and maintenance, and possibly a mid-life refit, can be estimated as a ratio of the capital costs of a project. However, a more accurate estimate would require determining factors such as whether the maintenance will be carried out on-site or by towing the devices to the shore, and the frequency of routine repair and maintenance. Finally, the decommissioning costs are also an important part of the total expenditures of a wave energy project. Predicting the cost of decommissioning at the beginning of a project may be challenging since this cost is a result of activities that will take place at the end of the life of a wave energy converter array. The devices may be dismantled and recycled as raw material or they may be left on site and sunk to the bottom of the ocean to serve as shelter for marine life. Various research is carried out to assess the economics of wave energy projects. A method to analyze the economics of wave energy generation that can also be utilized to support the investment decisions for developing wave energy converters and arrays is presented (Teillant et al., 2012). The proposed method comprises the calculation of both the energy generated by the devices and several economic indicators. Operational costs are evaluated by carrying out detailed operational scenarios. The method is tested by simulating a WEC array with 100 devices deployed near the Irish West Coast. The performance analysis of two wave energy converters is carried out by taking into account both the energy capture and the costs (O'Connor et al., 2013). The form of WECs, wave climate at different locations, and use of scaled versions of the devices are considered for comparison. The cost factors that affect the economics of wave energy are reviewed and the preliminary costs, operation and maintenance costs, and decommissioning costs are described and their reference values and ratios of total or capital costs are given (Astariz & Iglesias, 2015). Additionally, formulas to calculate levelized cost and initial cost are also presented. Finally, the performances of different wave energy converters are compared based on the levelized cost of energy and their economic competitiveness is discussed. The economic modeling of wave energy is studied by carrying out a spatial analysis of the Levelized Cost of Energy through a Geographical Information System (GIS) (Castro-Santos et al., 2015). Initial costs and operation and maintenance costs are considered and the sensitivity of the analysis is evaluated by utilizing different discount rates. Several physical restrictions are also considered and the method is tested for an oscillating water column (OWC) off the Portuguese coast. The levelized cost of wave energy is analyzed by taking different values of each cost and by considering different capacity factors and discount rates. The results are compared to those of other renewable and non-renewable energy sources, and it's concluded that wave energy is more expensive than all others since it is still an immature technology. The influence of variable operation and maintenance costs, learning curve, and externalities are also considered by carrying out a sensitivity analysis (Astariz & Iglesias, 2016). The levelized cost of energy of different wave energy converters is evaluated for different locations and cost reduction methods are studied to achieve economic competitiveness by reaching a target price (Chang et al., 2018). The feasibility of deploying wave energy farms off the coast of Portugal is studied by taking into account the geographical features such as wave climate, distances between the wave energy farm and shore facilities, the bathymetry of the ocean sites, the energy capture performance of the wave energy farm, the cost of energy, and the restrictions that could affect the wave energy projects. The amount of energy captured and economic performance of the three WECs are evaluated and the best area to install wave energy converter arrays is determined (Castro-Santos et al., 2018). The expense of wave energy is generally calculated by estimating the cost of one component of a WEC and then utilizing a cost breakdown for the other components of the device. As a result, the accuracy of this approach depends on the available cost data. An alternative method is proposed by (Giglio et al., 2023) that the cost of energy is calculated by breaking the system into its all components and by estimating the cost of each component. This method is expected to reduce the uncertainties in the cost estimations. Detailed equations are given to calculate the cost of each component and a cost analysis is carried out for a WEC and the results are compared to other methods.

The performances of axisymmetric wave energy converters with several different float shapes and masses are evaluated by studying the energy captured in a year and the Levelized Cost of Energy in two sites in the Black Sea in this study. The combination of a large number of floats and power take-off system parameters resulted in many candidate WEC designs. First, the energy capture of each WEC design is calculated by considering all the sea states occurring in the considered sites. Then, the highest annual energy absorption achieved in two locations by all the floats considered is evaluated. Finally, the cost of energy is calculated by taking into account the CAPEX, OPEX, the decommissioning costs, and the annual energy produced.

This paper has four sections including the 'Introduction' section. The second section describes the methods that are utilized to compute the hydrodynamic parameters of the floats, the wave excitation forces, the motions of the floats, the energy captured by the WECs, and the cost of energy. The energy captured by the WECs in two locations along with a cost analysis are presented in the third section. The final section concludes the results of this study.

2. THE COMPUTATIONAL METHOD

The problem associated with wind-generated surface gravity waves is presented briefly as the following. The velocity potential of the uni-directional waves that propagate in the free surface of infinitely deep water is evaluated by satisfying the continuity equation, the linear free surface boundary condition, and the bottom boundary condition given in Eqs. (1)-(3), respectively, and thus, the potential function of the waves can be obtained in the complex form as given in Eq.(4) (Newman, 1989).

$$\nabla^2\emptyset = 0 \tag{1}$$

$$\frac{\partial^2\emptyset}{\partial t^2} + g\frac{\partial\emptyset}{\partial z} = 0, on\ z = 0 \tag{2}$$

$$\lim_{z\to-\infty}\frac{\partial\emptyset}{\partial z} \to 0 \tag{3}$$

$$\emptyset_I = \Re\left[\frac{igA}{\omega}e^{kz}e^{-i(kx-\omega t)}\right] \tag{4}$$

The wave excitation forces acting on the float of a WEC can be written as the sum of forces under the Froude-Krylov hypothesis and forces taking into account diffraction effects as given in Eq.(5), where m_i is the generalized unit normal vector as given in Eq. (6). The diffraction potential can be obtained by satisfying the body boundary condition as given in Eq.(7).

$$F_i = -\rho \iint_{S_B} \frac{\partial(\emptyset_I + \emptyset_D)}{\partial t} m_i dS, i = 1,2,\ldots,6 \tag{5}$$

$$m_i = \begin{cases} n_i, i = 1,2,3 \\ (r \times n)_{i-3}, i = 4,5,6 \end{cases} \tag{6}$$

$$\frac{\partial \emptyset_I}{\partial n} = \frac{-\partial \emptyset_D}{\partial n}, on\ S_B \tag{7}$$

The motions of a body in the free surface of the water generate waves that radiate outwards. The hydrodynamic force exerted on a body due to its oscillatory motions can be calculated by solving the radiation problem. The radiation problem is evaluated by employing a 3D panel method based on discretizing the body surface into triangular elements and distributing pulsating sources over these surface elements, whose potential function is given in Eq.(8) (Wehausen & Laitone, 2002). The wave excitation forces and radiation forces are calculated by utilizing in-house computer programs developed by employing MATLAB and Fortran software.

$$\emptyset = \frac{-\sigma}{4\pi}\left[\frac{1}{r} + \frac{1}{r'} + 2\nu PV \int_0^\infty \frac{e^{k(z+c)} J_0(kR)}{k-\nu} dk + i2\pi\nu e^{\nu(z+c)} J_0(\nu R)\right] \tag{8}$$

The hydrodynamic force exerted on the body by the surrounding fluid can be calculated as given in Eq.(9). The body surface and the inner water plane area are discretized into a sufficient number of panels such that the numerical results converged and the irregular frequencies are suppressed. Additionally, the source strength on each panel is assumed constant throughout the calculations. The details of the evaluation of the potentials of the body motions ($\emptyset_j$) can be found in (Erselcan & Kükner, 2017) and (Erselcan & Kükner, 2020).

$${F_{ij}}^{Rad} = -\rho \iint_{S_B} \left(\frac{\partial \emptyset_j}{\partial t}\right) \zeta_j m_i dS, i,j = 1,2,\ldots,6 \tag{9}$$

The added mass can be obtained by dividing the real part of the force calculated by Eq.(9) when the amplitude of the motions is unitary by the square of angular frequency (ω^2) and the hydrodynamic damping can be computed by dividing the imaginary part by ($-\omega$).

The heave displacement of the float of an axisymmetric WEC is computed by solving the equation given in Eq.(10) in the time domain (Bruzzone & Grasso, 2007). This equation is solved by employing 4th order Runge-Kutta method and a family of Runge-Kutta-Nyström methods with 5th, 6th, and 7th orders of accuracy (Fehlberg, 1974). The evaluation of the equation is carried out by employing different time steps and random wave phase angles and the results obtained by each method are compared to each other and the differences between them are presented in detail (Erselcan & Kükner, 2020).

$$(M + A_{33}{}^{\infty})\ddot{x}_3(t) + \rho g S x_3(t) + \int_{-\infty}^{t} h_{33}(t-\tau)\ddot{x}_3(t)d\tau = F_3{}^{FK}(t) + F_3{}^{D}(t) + F_{PTO}(t) \quad (10)$$

The energy captured by the WECs in a year (AEP) is computed by taking the sea states occurring off the coasts of Sinop and Hopa into account. A total of five sea states at each location, one of which is a fully developed sea state while the others are developing sea states are considered in this study. The spectral functions, the mean values of the parameters corresponding to each sea state, and the occurrence rates of these sea states are given in (Yılmaz, 2007) and (Yılmaz & Özhan, 2014). The energy captured by each WEC in a given sea state is calculated by integrating the instantaneous power over time as given in Eq.(11) and the AEP is the sum of the total energy captured in all sea states occurring during a year as given in Eq.(12),

$$E = \int_{0}^{T} P(t)dt \quad (11)$$

$$AEP = \sum_{i=1}^{N_{SS}} E_{i,1H} C_i \quad (12)$$

where $E_{i,\,1H}$ is the average energy captured by a WEC in 1 hour in a given sea state, Ci is the total hours that a sea state occurs in a year, and N_{SS} represents the number of sea states occurring in the considered sites.

The wave energy converters analyzed in this study are considered to have a hydraulic power take-off system. The power take-off system comprises a double-acting hydraulic cylinder, a group of check valves, high and low-pressure hydraulic accumulators, a flow control valve, and a hydraulic motor that runs a generator. The hydraulic cylinder is rigidly connected to the float and it pumps the hydraulic fluid by the heave motion of the float. The hydraulic fluid is first pumped into the high-pressure (HP) accumulator. The high-pressure accumulator is discharged after it is fully charged. A flow control valve regulates the flow of the fluid, such that the HP accumulator is discharged at a constant flow rate. The flow of hydraulic fluid and the pressure differential between the accumulators runs the motor and the electric generator generates electricity. A detailed schematic of the power take-off (PTO) system is shown in Figure 1 and the modeling of the PTO system can be found in (Erselcan & Kükner, 2017) and (Erselcan & Kükner, 2020).

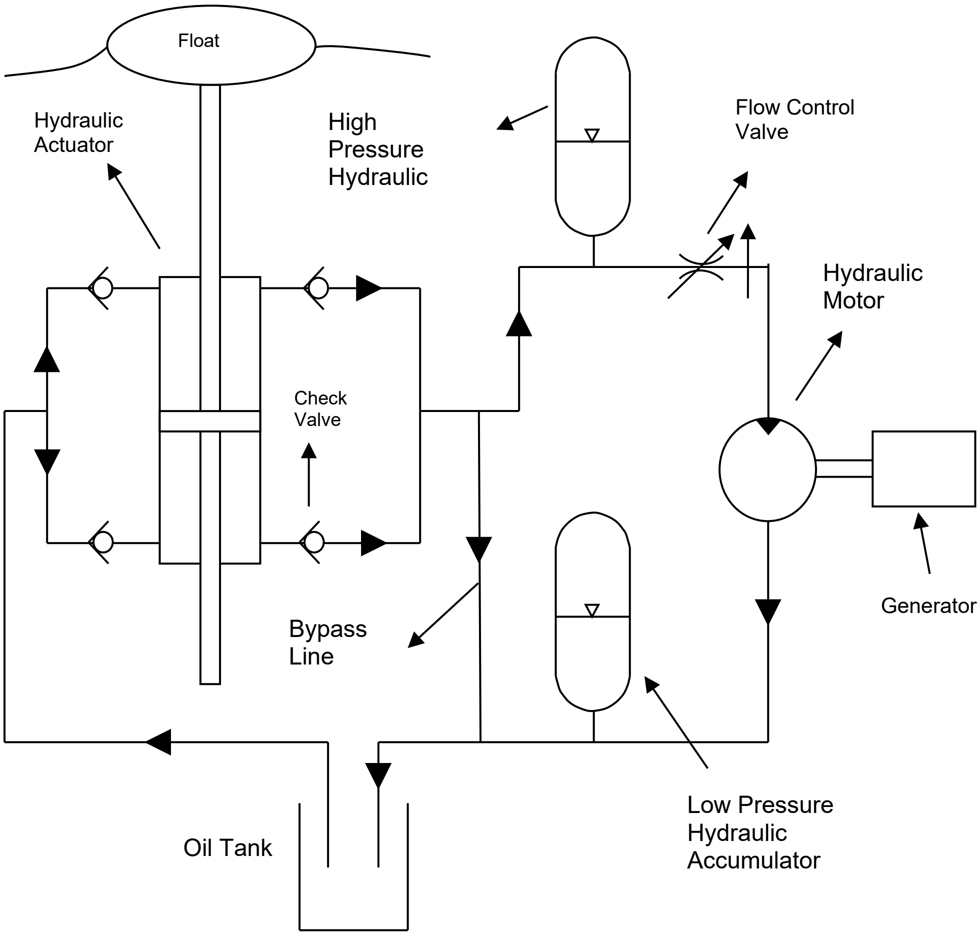

Figure 1. Hydraulic Power Take-Off (PTO) System.

The expense of the energy is evaluated by calculating the Levelized Cost of Energy (LCOE) of each WEC. The LCOE is computed by evaluating Eq.(13) as given in (SI Ocean, 2013).

$$LCOE = \frac{SCI + SLD}{87.6 \cdot LF} \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} + \frac{OM}{87.6 \cdot LF} \tag{13}$$

The capital costs (SCI), the decommissioning costs (SLD), the discount rate (r), the lifetime of the array (n), and the yearly operating and maintenance costs are considered to evaluate the LCOE of a wave energy converter array. The capital costs mainly comprise the cost of the project, the costs of manufacturing the devices, foundations, and moorings, the cost of installation, and the cost of decommissioning. The operating costs are comprised of the costs of operation, maintenance, insurance, and transmission charges. The calculation of capital costs depends on calculating the cost of material used to manufacture the devices. Thus, the amount of material used to manufacture the components of a WEC such as the float, mooring lines, and the body of the device should be estimated. Several cost breakdowns of wave energy converters as a ratio of either capital cost or the total costs are shown in Table 1 and are given in (Bosserelle et al., 2015; Guo et al., 2023; Piscopo et al., 2017; SI Ocean, 2013). Finally, all the steps of the analyses are visualized by a flowchart as seen in Figure 2.

	Cost Division 1 (CD-1)	Cost Division 2 (CD-2)	Cost Division 3 (CD-3)	Cost Division 4 (CD-4)
Structure	31%	27%	53.1%	38.2%
PTO	22%	49%	13.2%	24.2%
Infrastructure	5%	4%	3.6%	8.3%
Installation	18%	13%	10.2%	10.2%
Mooring	6%	5%	5.4%	19.1%
Project Management/Permits	---	2%	14.5%	---
O&M	7%	4%	6.3%	5%

Table 1. Wave energy converters cost breakdowns.

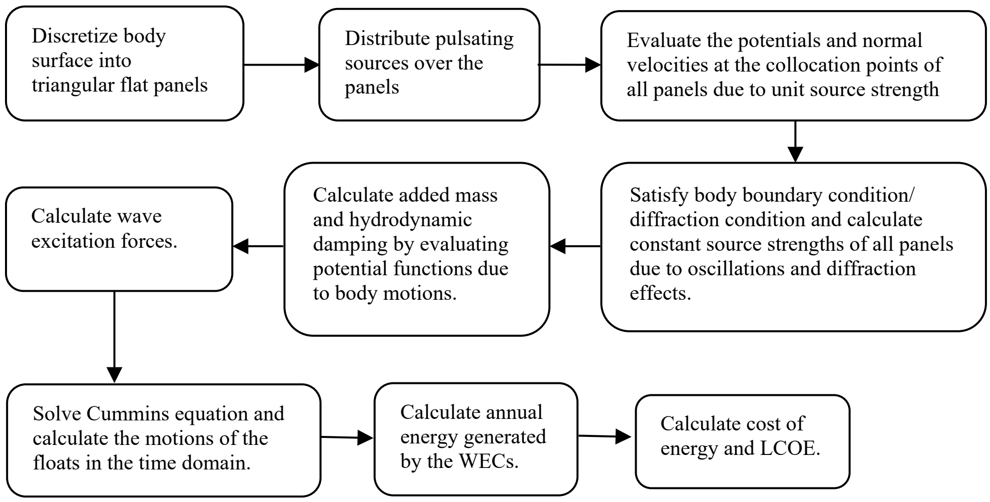

Figure 2. Flowchart of the analysis method.

3. RESULTS

The research aims to design an axisymmetric WEC and to optimize it for the best operation under the action of irregular waves observed in the target areas throughout the year. Thus, 5 different axisymmetric bodies, a half-immersed ellipsoid (SE), a half-immersed elliptic paraboloid (SEP), a cylinder (CYL), a cone (CONE), and a Berkeley Wedge (BW) which can be seen in Figures 3-7, are chosen as the floats of the point absorber WEC. Additionally, 3 different displacement masses in seawater are determined for each float type and each float is designed to have 5 different draft-to-radius ratios. The floats weigh the same as semi-spheres (M4, M5, and M6) whose radii are 4, 5, and 6 meters, respectively. A total of five ratios of draft to radius range equally from 0.2 to 1. As a result, a total of 75 different float geometries are considered for the analyses to design the most suitable WEC in each location. Moreover, 4 different power take-off system parameters, the hydraulic piston's cross-sectional area, the greatest working pressure of the HP accumulator, flow rate while discharging, and the discharge duration, are also considered for the design and the optimization of the WEC. The values of the hydraulic piston's cross-sectional area, the highest gas pressure of the HP accumulator, the flow rate while discharging, and the discharge duration range from 0.01 m^2 to 0.2 m^2, from 50 Bars to 150 Bars, from 0.01 m^3/s to 0.5 m^3/s, and from 10 seconds to 100 seconds, with increments of 0.01 m^2, 10 Bars, 0.01 m^3/s, and 10 seconds, respectively. The optimization of the power take-off system is carried out simultaneously along with the optimization of the floats.

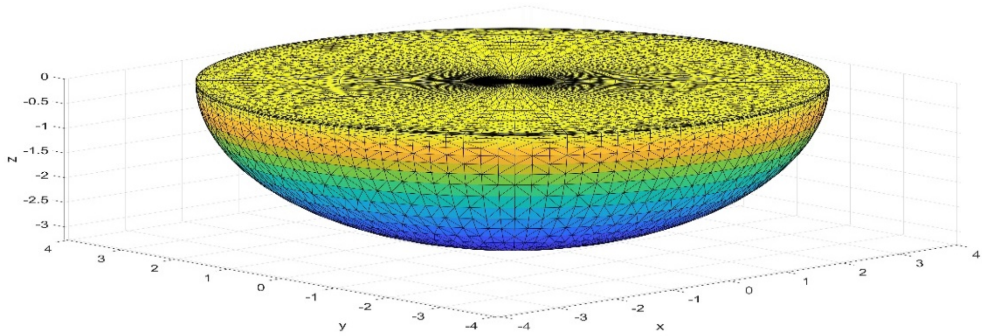

Fig. 3. Semi Ellipsoid (SE) Float.

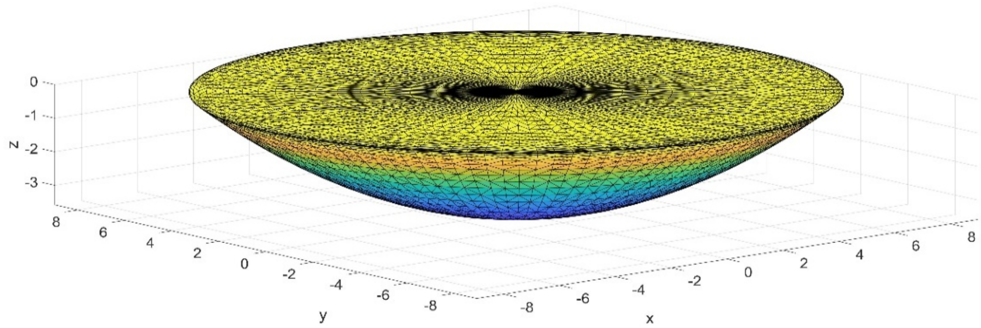

Figure 4. Semi Elliptic Paraboloid (SEP) Float.

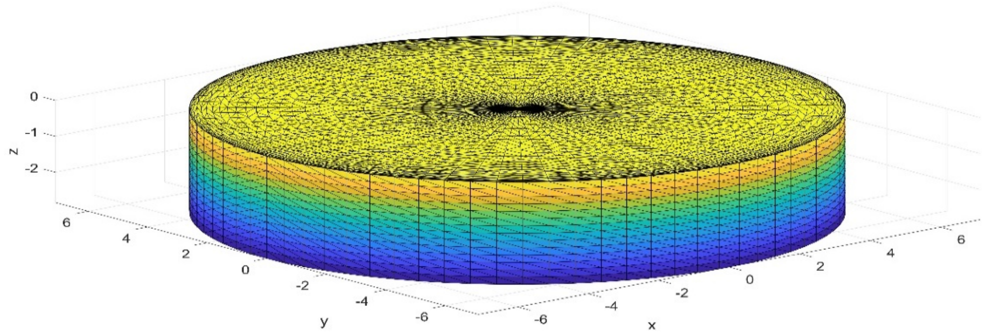

Figure 5. Cylinder (CYL) Float.

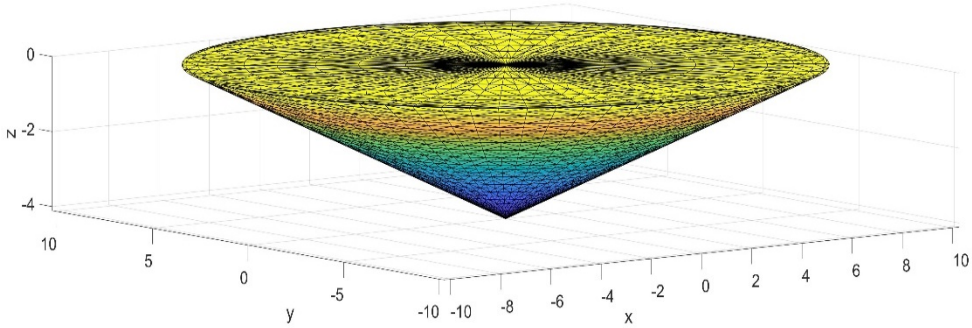

Figure 6. Cone Float.

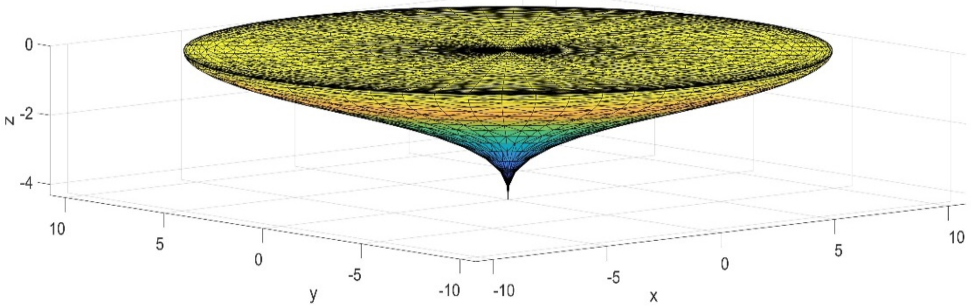

Figure 7. Berkeley Wedge-Shaped (BW) Float.

The coupling of every float with a set of PTO working parameters resulted in a point absorber WEC design and the energy captured by each WEC is computed by evaluating the oscillatory motion of the float in the time domain. The comparisons of the energy captured in a year by the WECs at each location are presented in Figure 8 and Figure 9. The results are presented in a non-dimensional form such that the energy captured in a year by each WEC is divided by the maximum energy captured in a year in each location. The results indicate that the maximum energy is captured when the ratio of the draft to the radius of each float is the smallest in both locations. In addition, all WEC designs with different float geometries show a similar trend that when the ratio of draft to radius increases, the energy captured decreases. Moreover, the Berkeley Wedge-shaped float (M6) can absorb the highest energy from the waves both in Sinop and Hopa. These results may indicate that designing a WEC with an oblate and a heavy float ensures absorbing the highest energy. However, an analysis of the cost of the energy is essential to be carried out and the least unit energy cost should be determined. As a result, the cost of the energy captured is evaluated and the results are presented in Figure 10 and Figure 11 in non-dimensional form that the energy cost achieved by each WEC is divided by the highest cost. The results show that the least unit energy cost is not achieved by the WECs that generate the greatest energy. The least unit energy cost is achieved when each WEC with a different float geometry has a different draft-to-radius ratio in both locations. Additionally, it can also be concluded that a light WEC can be more economical than that of a heavy one.

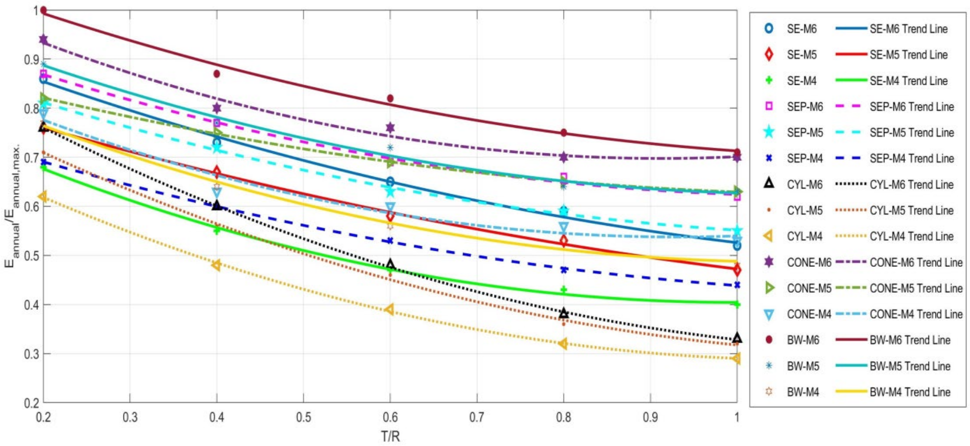

Figure 8. The comparison of the energy captured in a year by all WECs in Sinop.

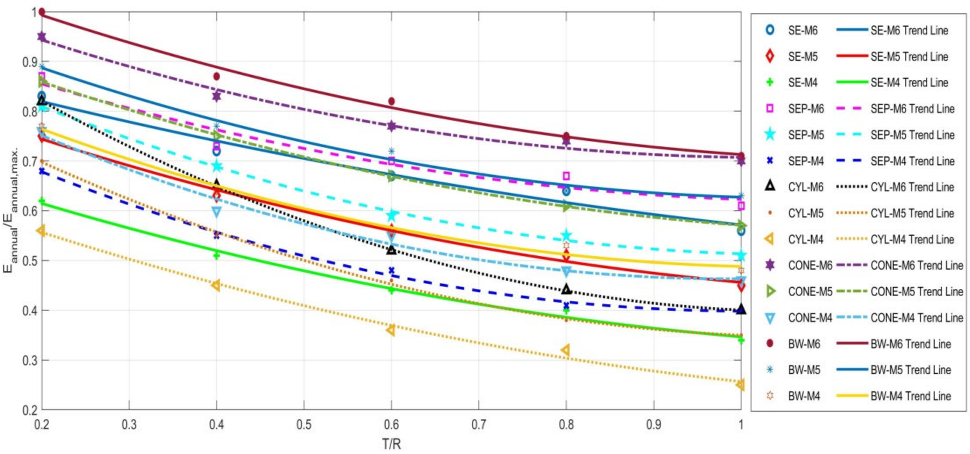

Figure 9. Comparison of the energy captured in a year by all WECs in Hopa.

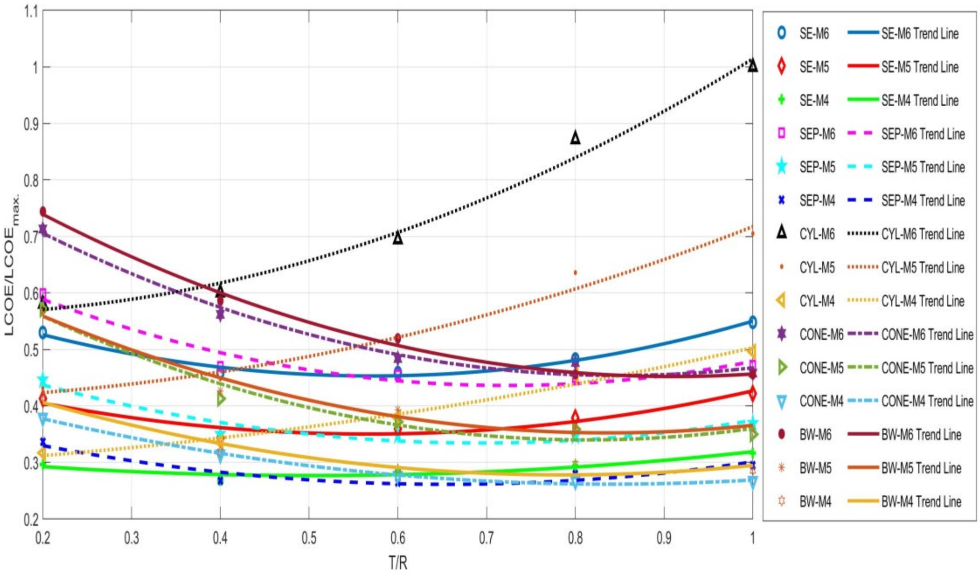

Figure 10. Comparison of the LCOE of all WECs in Sinop.

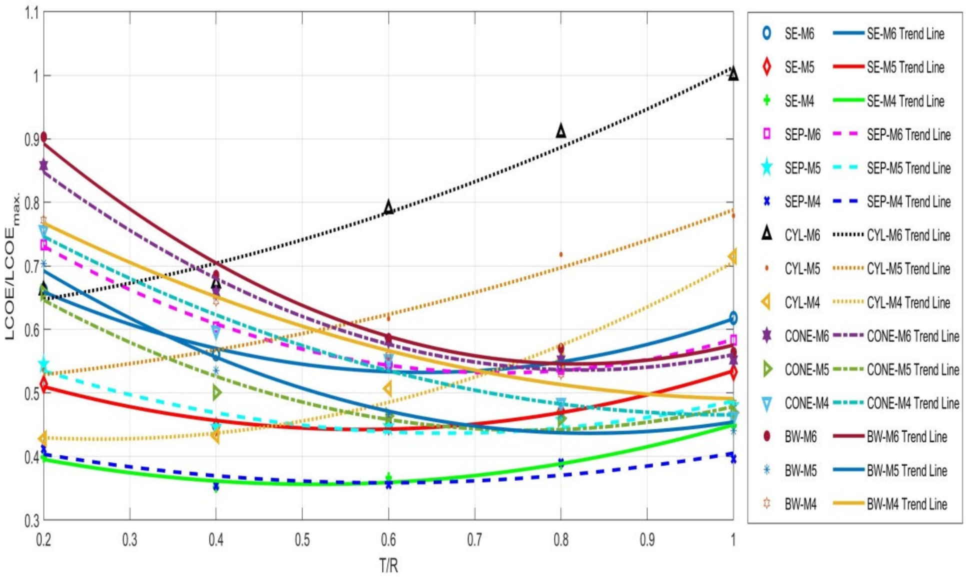

Figure 11. Comparison of the LCOE of different WECs in Hopa.

The sensitivity of the cost analysis is carried out by utilizing different cost breakdowns, device lifetimes, and discount factors. The cost breakdowns presented in Table 1 are utilized in the cost analyses of the WECs designed in the current study. The device lifetime is taken between 20 and 30 years and increased by 1 year for each analysis. The discount factor is taken between 1% and 25%. The analyses showed that the LCOE changed significantly when different cost breakdowns were used in the cost analyses. Additionally, increasing the discount factor resulted in an increase in the LCOE for any given device lifetime. The rate of increase in LCOE due to increasing discount factor differs for different cost breakdowns, which changes approximately between 3% and 13% for every increase of the discount factor by 1% at any given lifetime of the device as shown in Figure 12. Similar results showing that the LCOE increases with an increasing discount factor are presented by (Chang et al., 2018). Moreover, the LCOE increases significantly when the discount factor increases substantially. Figure 13 shows that if the discount factor is increased from 1% to 25%, the LCOE increases approximately by 150-300% when the device lifetime is taken 20 years and approximately by 190-460% when the device lifetime is taken 30 years. However, LCOE decreases with increasing lifetime for any given discount factor as shown in Figure 14. The decrease in LCOE is evaluated by comparing the LCOEs indicating that if the financial risks are low and the devices can be operational for long periods, then the cost of energy can be reduced. Finally, the most significant result is that the ratio of the LCOE of the devices to the maximum LCOE at each location remained the same as shown in Figures 10-11, despite the changes in the cost breakdown, device lifetime, and discount factor.

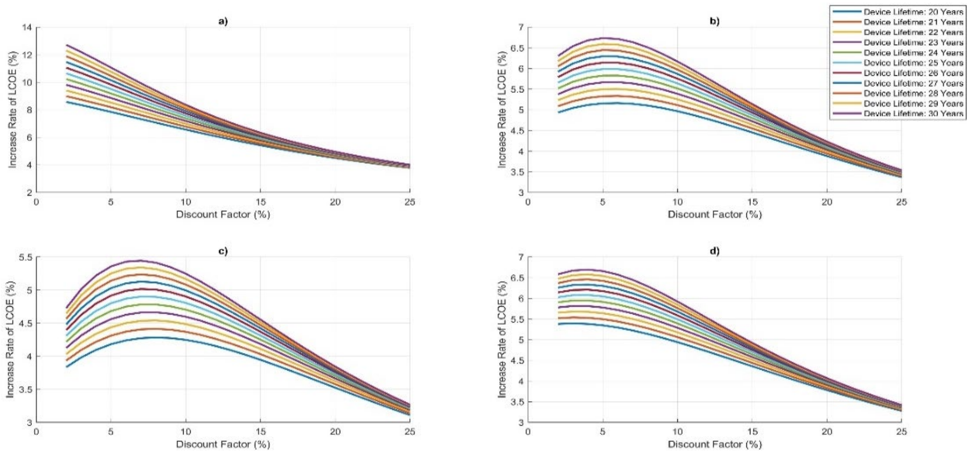

Figure 12. Increase rate of LCOE by 1% increase of discount factor, a) CD-1, b) CD-2, c) CD-3, d) CD- 4.

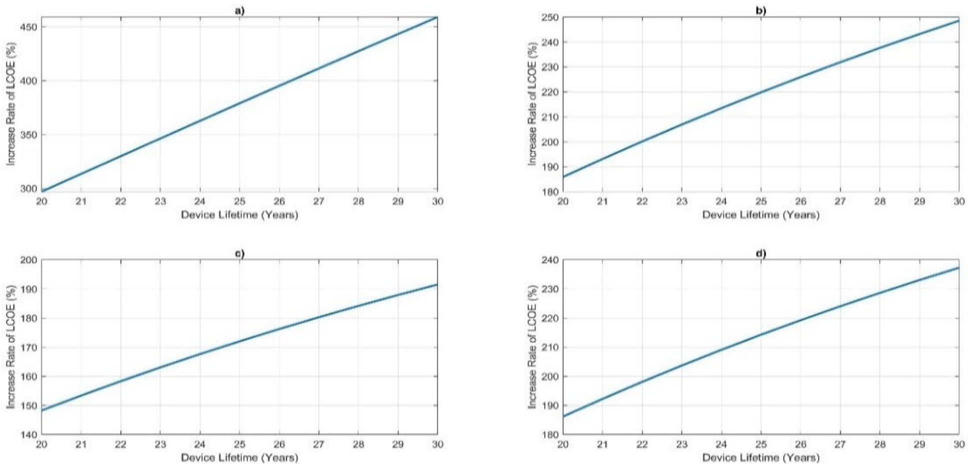

Fig. 13. Increase rate of LCOE due to the change of discount factor from 1% to 25% at different device lifetimes, a) CD-1, b) CD-2, c) CD-3, d) CD-4.

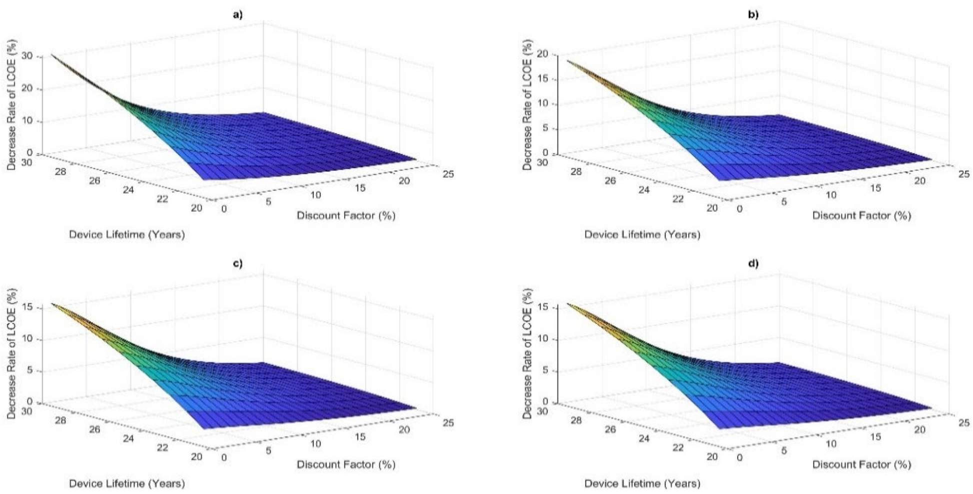

Figure 14. Decrease of LCOE at different device lifetimes for a given discount factor, a) CD-1, b) CD-2, c) CD-3, d) CD-4.

The results presented in Figures 3-6 are obtained by analyzing wave energy converters assuming they stand alone. However, wave energy converter arrays will be needed to generate utility-scale energy to power many living and working spaces.

The energy capture and cost analyses show that there may be more than one optimum wave energy converter design that is suitable for constructing an array. While some of these designs can capture more power than others, their cost of unit energy can be higher than those whose energy capture is low. Thus, it should be determined that an array would either consist of a large number of wave energy converters with low energy cost or a small number of devices with high energy cost for a given total energy capture.

Constructing a WEC array requires the evaluation of the influences of array layout, the number of WECs, the gap width, and the incident wave angle with respect to the fundamental orientation of the array on the energy capture. Each of these factors affects the wave forces acting on each WEC, so the energy capture of the devices within the array differs from that of a single isolated device. As a result, the total energy absorption of an array will be different than that of the same number of single isolated wave energy converters due to the constructive or destructive hydrodynamic interactions between the waves and the WECs. Consequently, the total efficiency of an array can be measured by evaluating a q-factor (Babarit, 2013) based on the yearly energy production of the array and that of a single standing wave energy converter as given in Eq.(14),

$$q_{Array} = \frac{E_{Annual}}{N_{WEC} E_{Annual,Isolated}} \tag{14}$$

where E_{Annual} is the energy produced in a year by an array, N_{WEC} is the number of WECs in the array, and $E_{Annual,\ Isolated}$ is the annual energy production of a single standing WEC.

4. CONCLUSION

The energy captured by different WECs that are considered for deploying in two locations near the Turkish coast of the Black Sea and the unit energy expense is evaluated by taking into account various floats, float masses, PTO parameters, sea states, cost breakdowns, discount factors, and device lifetime. It is determined that the energy captured can be increased by increasing the mass of the float. Additionally, if the ratio of the draft to the radius of the floats reduces, then the energy captured by all the WECs increases. As a result, it can be concluded that more energy can be captured by increasing a float's mass and by making it more oblate.

The LCOE of each WEC design considered in the current research is calculated to evaluate the energy expenses. The results indicate that the most economical WECs are not able to absorb the highest amount of energy. The LCOEs of all the WECs except with cylinder-shaped floats reach their minimum values at a ratio of draft to radius within the considered range. However, the WECs with cylinder-shaped floats have minimum LCOE values while their draft-to-radius ratios are 0.2. Moreover, the results show that the LCOE decreases with decreasing mass of the float, which indicates that manufacturing smaller WECs by using less material may help reduce the cost of energy. Furthermore, the effects of different cost breakdowns, discount factors, and device lifetime on the LCOE are studied. Using different cost breakdowns that are proposed in different studies results in different initial, operation and maintenance, decommissioning, and total costs. The main reason for such a differentiation in the costs is that the cost of each component and the rate of the cost of each component to the total cost in different WEC designs differ from each other. Thus, using a cost breakdown of a similar type of WEC to estimate the cost of energy of a particular type of wave energy converter may result in more accurate cost estimates. On the other hand, although different cost breakdowns result in different LCOEs, it is determined that the ratios of the LCOEs of different WECs to the highest LCOE remain the same.

The effect of the discount factor and the device lifetime applied in the calculation of the LCOE are also studied and the results indicate that an increase in discount factor causes the LCOE to increase for any given device lifetime. However, the LCOE decreases with increasing device lifetime for any given discount factor.

Consequently, the results and conclusions obtained in this study reflect the output of a single-standing wave energy converter. However, many devices will be installed in proximity to form arrays and hydrodynamic interactions will change the power capture of each wave energy converter in an array. Thus, further work that will take the hydrodynamic interactions among the WECs in an array into account is required to assess the energy capture and economic performances of wave energy converter arrays.

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