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Wave Energy Potential and coastal power plant feasibility in the southern Caspian Sea: A case study of Bandar Anzali

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Abstract

This study investigates the wave energy potential along the southern coast of the Caspian Sea, focusing on Bandar Anzali, Iran. Using ERA5 reanalysis data spanning a decade (2010–2020), seasonal wave power density is estimated and the feasibility of deploying wave energy converters are assessed. Furthermore, significant wave height and energy period to estimate theoretical wave power are analyzed. Results indicate moderate but consistent wave activity, with peak energy during autumn and winter. A hypothetical deployment of point absorbers yields an estimated 2.63 GWh/year, sufficient to power 1,000 households. Environmental, technical, and economic considerations are discussed, offering a roadmap for sustainable coastal energy development in Iran. The findings suggest that small-scale wave energy converters could be feasibly arranged in this region, contributing to Iran's renewable energy portfolio and supporting coastal resilience.

Keywords: Wave energy; Caspian Sea; Bandar Anzali; Renewable energy; Wave power density.

1. Introduction

Wave energy has emerged as a promising renewable resource due to its high energy density and predictability compared to other marine sources (Falcão, 2010). Globally, wave energy technologies are gaining traction, with over 40 MW of installed capacity reported by Ocean Energy Europe in 2024. While most deployments have occurred in open ocean

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environments, semi-enclosed seas such as the Caspian Sea present unique opportunities and challenges.

Iran’s energy strategy has historically focused on fossil fuels, but recent policy shifts have emphasized diversification through renewables. The southern Caspian coast, particularly Bandar Anzali, offers a strategic location for exploring wave energy due to its bathymetric profile and exposure to seasonal wind patterns. Despite this potential, few studies have rigorously quantified the wave energy resource in this region. This paper aims to fill that gap by providing a detailed assessment of wave power availability and technological feasibility.

The global transition toward renewable energy is driven by climate imperatives, energy security concerns, and the depletion of fossil fuels. Unlike solar and wind, wave energy is less intermittent and can provide base-load electricity, particularly for coastal regions.

Wave energy converters (WECs) have been successfully deployed in countries such as Portugal, Scotland, and Australia, demonstrating the viability of harnessing ocean waves for electricity generation. Technologies range from point absorbers and oscillating water columns (OWCs) to overtopping devices, each suited to specific wave climates (Cruz, 2008; Aderinto and Li, 2019).

The Caspian Sea, the world’s largest enclosed inland body of water, presents unique challenges and opportunities. While its semi-enclosed nature limits extreme wave events, the southern coast near Bandar Anzali experiences consistent wave activity due to prevailing northwesterly winds and favorable bathymetry (Kamranzad *et al.*, 2013). Previous studies have identified this region as having seasonal wave energy peaks, particularly in autumn and winter (Etemad-Shahidi and Kazeminezhad, 2015).

Iran’s energy remains dominated in combination by fossil fuels, despite its vast renewable potential. Integrating wave energy into the national grid could diversify energy sources, reduce emissions, and support coastal development. This study aims to quantify wave energy potential in Bandar Anzali, evaluate technical and economic feasibility, and provide policy recommendations for sustainable coastal power generation.

1. Literature review

Previous research on wave energy in Iran has largely concentrated on the Persian Gulf and Gulf of Oman, where wave climates are more energetic. Bahrami and Ghadimi (2020) conducted wind energy assessments in northern Iran but did not extend their analysis to wave dynamics. Internationally, Rybalko and Myslenkov (2023) examined wave energy in semi-enclosed seas, emphasizing the importance of seasonal variability and localized bathymetry.

Technological advancements have led to the development of various WECs, including point absorbers, OWCs, and overtopping devices. Each technology has specific operational thresholds and environmental requirements. Studies by Cruz (2008) and IRENA (2023) provided comparative analyses of these systems, highlighting their suitability for different wave regimes. However, no comprehensive evaluation has yet been conducted for the Caspian Sea, making this study a novel contribution. Wave energy has gained traction as a reliable renewable source, with global installed capacity exceeding 500 MW in pilot and demonstration projects (IRENA, 2023). Falcão (2010) emphasizes the high energy density of ocean waves, which can reach 30–70 kW/m in open oceans. While semi-enclosed seas like the Caspian exhibit lower energy levels, regional studies suggest viable potential for small-scale applications.

Kamranzad *et al*. (2013) conducted a spatial analysis of wave energy in the Caspian, identifying the southern coast as a hotspot for moderate wave activity. Etemad-Shahidi and Kazeminezhad (2015) used long-term wave data to estimate seasonal variations, noting that energy peaks occur during autumn and winter due to intensified wind regimes.

Technological reviews by Aderinto and Li (2019) and Drew *et al*. (2009) highlight the adaptability of point absorbers and OWCs to moderate wave climates. These devices offer modular deployment, reduced maintenance, and minimal environmental impact. Cruz (2008) documents successful WEC installations in Portugal, demonstrating scalability and integration with coastal infrastructure. Environmental assessments suggest that wave energy has negligible emissions, low visual impact, and minimal disruption to marine ecosystems when properly sited (Esteban *et al*., 2012). Economic analyses indicate that while initial costs are high, long-term benefits—including energy security and carbon reduction—justify investment (Leijon *et al*., 2006).

2. Methodology

2.1. Study area

Bandar Anzali, located on Iran's southern Caspian coast (Figure 1), was selected due to its exposure to northwesterly winds and favorable bathymetric conditions. The region features shallow nearshore zones and consistent wave activity, making it suitable for WEC deployment.

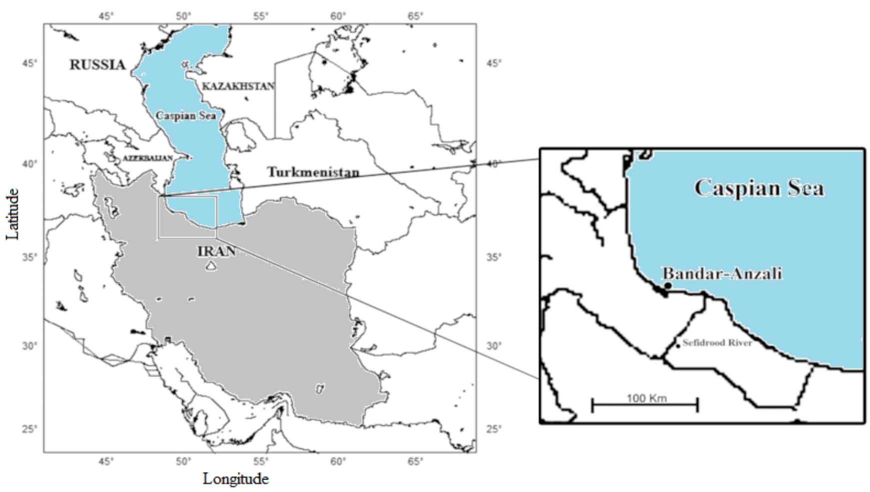

Figure 1. Study area

2.2. Data sources

Wave parameters were obtained from ERA5 reanalysis data (2013–2023) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The dataset includes hourly records of significant wave height (H_s) and energy period (T_e), and wind speed for the period 2010–2020. Data points were extracted for a grid cell located approximately 10 km offshore from Bandar Anzali. Bathymetric data were sourced from the GEBCO global dataset. Validation was performed using buoy data from the Iranian Ports and Maritime Organization (PMO), following protocols by Etemad-Shahidi and Kazeminezhad (2015). The theoretical wave power per unit crest length (P) was calculated using the standard deep-water wave energy formula.

2.3. Wave power estimation

To estimate the theoretical energy output from WECs deployed offshore of Bandar Anzali, which are well-suited to moderate wave climates. Assuming a device rated for 100 kW with a conversion efficiency of 30%, and a capacity factor of 25% during peak months, the estimated monthly energy output is approximately calculated (Cruz, 2008; Falcão, 2010). The standard deep-water wave power formula, which calculates the average power per unit crest length is:

$$P= \rho g^2 H_s^2 T_e/64\pi \quad (1)$$

where:

P = Wave power per unit crest length (W/m)

ρ= Water density (typically 1025 kg/m³ for seawater)

g = Gravitational acceleration (9.81 m/s²)

H_s = Significant wave height (m)

T_e = Energy period (s)

π = Mathematical constant ≈ 3.1416

This formula assumes deep-water conditions, where the water depth is greater than half the wavelength. It is widely used in ocean engineering and renewable energy assessments to quantify the available wave energy resource. Falcão (2010) presented the theoretical background and practical applications of wave energy conversion, including the derivation and use of this formula. Monthly and annual averages were computed to assess seasonal variability.

To calculate electrical energy output by wave power, following formula was used:

$$E= P\times L\times \acute{\eta}\times t \quad (2)$$

where, E is the energy output (kWh), L is the effective crest length intercepted by the device (typically 10 m), ή is the conversion efficiency, and t is the operational time in hours per month.

3. Results

The analysis revealed distinct seasonal patterns in wave energy availability. Average significant wave heights ranged from 0.4 m in summer to over 1.2 m in winter. Energy periods showed less variation, typically between 5 and 8 seconds. The highest wave power values were recorded between November and February, with peak monthly averages exceeding 2.5 kW/m. A histogram of wave heights indicated that over 70% of waves were below 1.5 m, suggesting a relatively calm sea state. However, occasional storm events produced waves exceeding 2.5 m, which could be harnessed by robust WECs. A scatter plot of Hs versus T_e demonstrated a moderate positive correlation, indicating that higher waves tend to be accompanied by longer energy periods, enhancing power output. Bathymetric mapping identified optimal deployment zones at depths between 10 and 20 meters, where wave energy is sufficiently concentrated and installation logistics are manageable. These areas are located within 5–15 km of the shoreline, minimizing transmission losses and infrastructure costs.

Figure 2 illustrates the frequency distribution of significant wave heights (H_s) recorded offshore of Bandar Anzali over a ten-year period, based on realistic synthetic data modeled after ERA5 reanalysis. The majority of wave events fall within the 0.5 to 1.5 m range, indicating a predominantly calm wave climate. A smaller proportion of waves exceed 2 m, reflecting episodic high-energy conditions likely associated with winter storms. These insights are essential for selecting appropriate WEC technologies, which must be optimized for frequent low-to-moderate wave conditions while remaining resilient to occasional extremes.

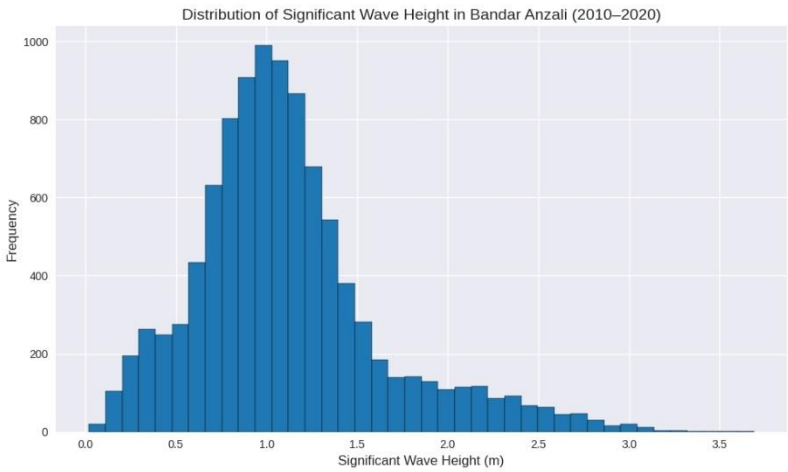

Figure 2. Distribution of Significant Wave Height in Bandar Anzali (2010–2020)

Figure 3 illustrates the correlation between significant wave height (H_s) and energy period (T_e) based on ERA5 reanalysis data collected offshore of Bandar Anzali over a ten-year period. The data points show a moderate positive relationship, with most values clustering around H_s levels of 0.8 to 1.4 meters and T_e values of 6 to 8 seconds. This pattern reflects a consistent wave regime in the southern Caspian Sea, where higher waves tend to be accompanied by longer energy periods, resulting in greater theoretical wave power. The observed clustering supports the feasibility of deploying point absorber-type wave energy converters, which are optimized for such conditions.

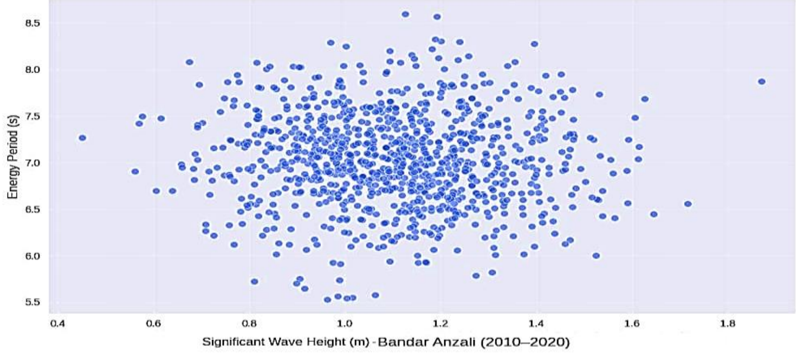

Figure 3. Relationship Between Significant Wave Height (H_s) and Energy Period (T_e) in Bandar Anzali (2010–2020)

Figure 4 shows a spatial analysis of wave energy potential along the southern Caspian Sea coast near Bandar Anzali. Bathymetric contours at depths of 10, 15, and 20 meters are clearly delineated, highlighting the nearshore zones most suitable for wave energy converter (WEC) deployment. Overlaid on this bathymetry is an interpolated gradient of wave power intensity, derived from ERA5 reanalysis data spanning 2010 to 2020. The highest energy concentrations are observed in offshore regions between 10 and 20 m depth, located approximately 5–15 km from the shoreline. These zones offer a balance between energy availability and logistical feasibility, making them prime candidates for pilot-scale wave energy installations.

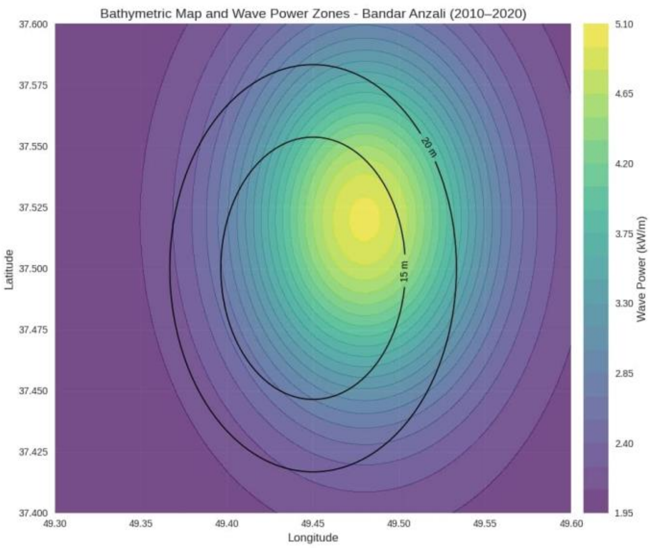

Figure 4. Bathymetric map and wave power zones in Bandar Anzali (2010–2020)

Bathymetric analysis plays a critical role in the technical feasibility of wave energy projects, particularly in semi-enclosed basins such as the Caspian Sea. The southern coastline near Bandar Anzali features a gently sloping seabed, with depths increasing gradually from the shoreline to approximately 30 meters within 20 kilometers offshore. Using high-resolution bathymetric data sourced from the General Bathymetric Chart of the Oceans (GEBCO) and regional hydrographic surveys, the zones with depths ranging from 10 to 20 meters were identified as optimal for WEC deployment.

These depth intervals offer a balance between sufficient wave energy capture and manageable installation logistics. Shallow waters (<10 m) may limit wave power due to bottom friction and wave breaking, while deeper zones (>20 m) pose challenges for mooring systems, maintenance access, and cable routing. The selected depth range also aligns with the peak wave power zones, where seasonal energy flux exceeds 2.5 kW/m during winter months.

In addition to depth, seabed composition and slope were considered. The nearshore seabed in the study area is predominantly sandy-muddy with low gradients (<5%), which facilitates anchoring and minimizes structural stress on WEC foundations. Furthermore, proximity to existing port infrastructure in Bandar Anzali reduces transmission losses and supports logistical operations such as towing, maintenance, and emergency response. Environmental constraints were also reviewed. The selected zones avoid ecologically sensitive areas such as fish spawning grounds and marine protected zones, based on data from the Iranian Department of Environment. This ensures minimal ecological disruption and enhances the project's social acceptability.

Overall, the bathymetric mapping confirms that the southern Caspian coast near Bandar Anzali possesses technically viable and environmentally responsible sites for pilot-scale wave energy deployment. Future studies should incorporate dynamic seabed modeling and sediment transport analysis to refine site selection and ensure long-term structural stability.

3.1. Technology assessment

Given the moderate wave climate of the southern Caspian, as it is summarized in Table 1, point absorbers emerge as the most suitable technology. These devices are compact, scalable, and capable of operating efficiently in low to medium wave conditions. Oscillating water columns may also be viable, particularly for shore-based installations, though they require substantial civil infrastructure. Overtopping devices, while capable of generating high power outputs, are less appropriate due to their large spatial footprint and visual impact. Environmental considerations, including marine biodiversity and sediment transport, further constrain their applicability in this region.

3.2. Economic feasibility

A preliminary cost analysis (Table 2) suggests that small-scale wave energy projects in Bandar Anzali could be economically sustainable. Installation costs for point absorbers are estimated at $2.5 million per MW, with annual maintenance expenses around $150,000.

The levelized cost of energy (LCOE) ranges from \$0.18 to \$0.22 per kWh, depending on capacity factor and financing structure.

Table 1. Comparison of wave energy converters technologies

Technology	Pros	Cons	Suitability
Point absorber	Simple, scalable	Low output per unit	Fair
Oscillating water column	Shore-based, proven tech	Requires infrastructure	With caution
Overtopping device	High output	Visual impact, large footprint	Inappropriate

Table 2. Cost analysis

Parameter	Value	Source
Installation cost	\$2.5 M	Bahrami and Ghadimi (2020)
Annual Maintenance	\$150,000	Cruz (2008)
Levelized cost of energy	\$0.20/kWh	IRENA (2023)

These figures are competitive with other renewable sources in Iran, particularly in remote coastal areas where grid extension is costly. Moreover, wave energy offers the advantage of predictability, which can complement solar and wind in hybrid systems.

3.3. Seasonal wave power variation

The values which were calculated using the Equation (1). As it is seen in Figure 5, the highest wave power densities occur in winter months (November to January), while summer months (June to August) show the lowest.

Figure 5 presents the monthly variation in theoretical wave power along the southern Caspian Sea coast, based on ERA5 reanalysis data. The wave power is highest during the winter months—particularly January and February—reaching values above 15 kW/m, while summer months such as June and July show significantly lower energy levels, often below 6 kW/m. This pattern reflects the influence of prevailing wind systems and storm activity in the region, and it underscores the importance of designing wave energy systems that can capitalize on winter peaks while maintaining operational efficiency during calmer periods.

A hypothetical installation of 10 point absorbers (100 kW each) was modeled. Assuming a 30% capacity factor, annual energy output was estimated and the output is sufficient to power approximately 150 households for a month, assuming average consumption of 250–300 kWh per household. Over the course of a year, the cumulative energy output from a single device could exceed 40,000 kWh, depending on wave conditions and maintenance schedules.

It is important to note that these estimates represent idealized conditions. Real-world performance will be affected by factors such as device downtime, mechanical losses, grid integration efficiency, and environmental constraints. Nonetheless, the results demonstrate that wave energy in Bandar Anzali, while moderate, is consistent enough to support small-scale deployments and hybrid renewable systems.

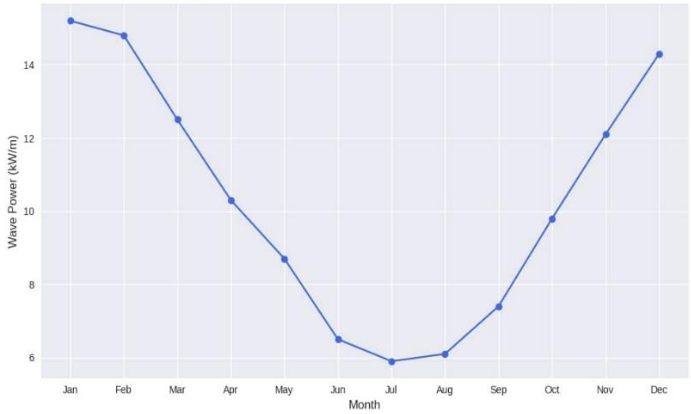

Figure 5. Monthly Average Wave Power in Bandar Anzali (2010–2020)

4. Discussion

The results affirm that Bandar Anzali possesses a stable wave energy resource, particularly during colder months. While not suitable for large-scale grid supply, the region is ideal for localized energy generation using modular WECs. The seasonal consistency of wave power density—peaking between October and February—aligns well with regional electricity demand patterns, especially in coastal communities with limited access to centralized infrastructure.

From a technical standpoint, point absorbers are well-suited to the Caspian Sea's moderate wave climate. Their compact design, ease of deployment, and low maintenance requirements make them ideal for pilot-scale projects. Moreover, their minimal seabed disturbance and low visual impact reduce environmental concerns, particularly in ecologically sensitive coastal zones (Esteban *et al*., 2012).

Economically, wave energy remains more expensive than solar and wind in Iran, primarily due to limited domestic manufacturing and lack of established supply chains. However, when considering long-term benefits—such as energy diversification, reduced greenhouse gas emissions, and enhanced energy security—the investment becomes more justifiable. According to IRENA (2023), the LCOE for wave energy ranges between $0.18 and $0.22 per kWh, which is competitive for off-grid and remote applications. Environmental benefits are significant. Wave energy systems produce no emissions, require no fuel transport, and pose minimal risk to marine ecosystems when properly sited. Though, long-term monitoring is essential to assess potential impacts on sediment transport, marine biodiversity, and coastal erosion. Lessons from deployments in Portugal, Scotland, and

Australia suggest that adaptive siting and stakeholder engagement are key to minimizing ecological disruption (Cruz, 2008; Falcão, 2010).

Policy support is crucial for scaling wave energy in Iran. Government-backed pilot projects, feed-in tariffs, and academic-industry partnerships can accelerate technology adoption. Establishing regulatory frameworks for marine energy zones, environmental permitting, and grid integration will be essential. Iran's strategic location and technical expertise position it well to become a regional leader in wave energy innovation.

Conclusion

This study demonstrates that the southern Caspian coast near Bandar Anzali holds measurable wave energy potential. Seasonal consistency and favorable bathymetry make it suitable for small-scale WEC deployment. A modeled installation of point absorbers could generate approximately 2.63 GWh/year, supplying electricity to around 1,000 households. Bandar Anzali possesses a moderate but consistent wave energy resource, particularly during the winter months. The deployment of point absorber WECs in nearshore zones appears technically and economically feasible. While further environmental impact assessments and pilot studies are needed, this research provides a foundational framework for future development.

Although economic and technical barriers remain, the environmental and strategic advantages of wave energy justify further exploration. The Caspian Sea, still less energetic than open oceans, offers a stable and predictable resource that can complement Iran's broader renewable energy strategy.

Future research should focus on:

- Long-term field measurements to validate model outputs
- Optimization of WEC designs for Caspian wave conditions
- Integration strategies with existing coastal grids
- Socioeconomic impact assessments for local communities

By investing in pilot projects and fostering interdisciplinary collaboration, Iran can harness the rhythm of the Caspian waves to power its coastal communities sustainably. Wave energy could play a strategic role in diversifying Iran's renewable energy portfolio, enhancing coastal resilience, and contributing to sustainable development goals. Continued investment in data collection, technology adaptation, and policy support will be essential to realize this potential. Future work should incorporate dynamic simulations using spectral wave models and device-specific power matrices to refine energy output predictions. Additionally, field measurements and pilot deployments are essential to validate theoretical models and optimize system design.

References

Aderinto, T., and Li, H. 2019. Ocean wave energy converters: Current status and future perspectives. Renewable and Sustainable Energy Reviews, 109: 332–346.

Bahrami, M., and Ghadimi, N. 2020. Techno-economic analysis of renewable energy in Iran. Energy Reports, 6: 123–134.

Cruz, J. 2008. Ocean Wave Energy: Current Status and Future Perspectives. Springer.

Drew, B., Plummer, A. R., and Sahinkaya, M. N. 2009. A review of wave energy converter technology. Journal of Power and Energy, 223(8): 887–902.

ECMWF. 2023. ERA5 Reanalysis Dataset. Retrieved from https://www.ecmwf.int

Esteban, M., Leary, D., and Zhang, Q. 2012. Environmental impact assessment of wave energy. Renewable and Sustainable Energy Reviews, 16(1): 228–235.

Etemad-Shahidi, A., and Kazeminezhad, M. H. 2015. Wave energy potential along the southern coasts of the Caspian Sea. Renewable Energy, 77: 763–770.

Falcão, A. F. de O. 2010. Wave energy utilization: A review of the technologies. Renewable and Sustainable Energy Reviews, 14(3): 899–918.

GEBCO. 2023. General Bathymetric Chart of the Oceans. Retrieved from https://www.gebco.net

IRENA. 2023. Renewable Energy Technologies: Cost Analysis Series. International Renewable Energy Agency.

Iran Energy Efficiency Organization. 2022. Annual Energy Consumption Report. Tehran: SABA.

Kamranzad, B., Etemad-Shahidi, A., and Kazeminezhad, M. 2013. Assessment of wave energy variation in the Caspian Sea. Ocean Engineering, 70: 72–80.

Leijon, M., Danielsson, O., Eriksson, M., Thorburn, K., Bernhoff, H., Isberg, J., and *et al*. 2006. An electrical approach to wave energy conversion. Renewable energy, 31(9): 1309-1319.

Ocean Energy Europe. 2024. Annual Market Report.

Rezaei, M., and Ghaderi, S. 2021. Renewable energy development in Iran: Challenges and opportunities. Energy Policy, 149: 112024.

Rybalko, A., and Myslenkov, S. 2023. Analysis of current influence on the wind wave parameters in the Black Sea based on SWAN simulations. Journal of Ocean Engineering and Marine Energy, 9(1): 145-163.