A Comparative Analysis Between Wave and Solar Energy for Sustainability in Coastal zones; Case Study: Alexandria Port, Egypt

Wael A. Kamel (1), Youssef K. Mahfouz (2), Ahmed M. A. Moussa (3), Youssef A. Ebeid (4)

(1) Department of Construction and Building Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, wael_kamel@aast.edu

(2) Department of Construction and Building Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, y.khairy@aast.edu

(3) Nile Research Institute (NRI), Qanater, Egypt, ahmed_moussa@hotmail.com

(4) Department of Construction and Building Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, Y.ebeid53@student.aast.edu

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1. **ABSTRACT:** The growing impact of carbon emissions, including rising sea levels and extreme weather, underscores the need for sustainable energy solutions, especially in coastal areas. This study compares solar and wave energy in Alexandria, Egypt, evaluating their costs and environmental feasibility. Utilizing Alexandria's high solar irradiance and promising wave energy potential, Solar Photovoltaic (PV) systems and Oscillating Water Column (OWC) wave energy systems are assessed. HOMER PRO software was used for solar modeling, while empirical formulas and MATLAB estimated wave energy production. Results show solar PV systems are more cost-effective, with a Levelized Cost of Energy (LCOE) of $0.01165/kWh and a CO_2 reduction of 26.3 million kg annually. In contrast, wave energy offers more consistent production and a larger environmental benefit (55 million kg CO_2 reduction per year), but with higher initial costs and an LCOE of $0.0472/kWh. The study concludes that while solar energy is more cost-effective, wave energy holds significant potential for long-term development in coastal zones like Alexandria.

2. INTRODUCTION

In the 21st century, technological advancements and population growth have increased energy demand. Fossil fuels like coal, oil, and natural gas were historically the primary energy sources, but their environmental impact, including greenhouse gas emissions, has contributed to climate change. To mitigate this, transitioning to renewable energy sources like solar, wind, and hydro power is essential, as they offer a sustainable, low-emission alternative against fossil fuels [1]. As countries commit to reducing emissions, Egypt has become a regional leader in renewable energy, leveraging its abundant solar and wind resources. By 2030, Egypt aims to generate 42% of its electricity from renewable sources. However, the specific breakdown for contributions from solar, wind, and hydropower has not been definitively detailed in public sources. As of 2024, renewable energy sources (including solar, wind, and hydropower) account for 11.5% of Egypt's electricity generation [2]. Key projects like the Benban Solar Park, the world's largest, and the Gulf of Suez wind farms highlight this vision. Despite challenges such as high infrastructure costs, plants like Benban and the Siwa Solar Plant are already powering thousands of homes, demonstrating Egypt’s progress [3].

Solar energy systems—on-grid, off-grid, and hybrid—are pivotal in this transformation. On-grid systems integrate with national grids, feeding excess power back into the system, while off-grid systems store energy for standalone use [4, 5]. Hybrid systems combine renewable and conventional energy sources, offering reliability and versatility, especially in remote areas. Innovations in solar panel technologies, such as PERC panels and flexible thin-film options, are enhancing efficiency and accessibility [6]. Egypt, with its 2,450 km coastline along the Mediterranean and Red Seas, offers significant wave energy potential, averaging 2.5 kW/m, particularly along the northern Mediterranean coast. While countries like the UK and South Africa achieve wave energy densities of 60–70 kW/m, Egypt’s potential presents a valuable opportunity for sustainable power generation. This complements Egypt's solar advancements and positions the country well for marine energy development. Wave Energy Converters (WECs), such as oscillating water columns and overtopping systems, effectively harness this potential, which classifies WECs by their motion type and structure [7, 8].

Oscillating Water Columns (OWCs) efficiently convert wave motion into electricity and are classified into fixed, breakwater-integrated, and floating designs [9]. Alexandria's Port plays a pivotal role in driving Egypt's trade and economic development, while its coastal location offers immense potential for wave energy. OWCs, which are already successfully used in Mediterranean Sea countries, are highly applicable for use in Egypt due to the region's favorable wave conditions [7]. Unlike solar and wind, wave or marine energy delivers consistent power with minimal loss over distances, making it a sustainable option for Egypt's energy needs [10,11]. This study highlights the complementary potential of solar and wave energy in Alexandria, advocating for their integration to address growing coastal energy demands sustainably.

3. METHOD AND TOOLS

Solar and wave energy, along with other renewables like wind and hydropower, are key to a sustainable energy future. Solar is cost-effective and versatile, while wave energy offers a reliable offshore source. A comparative analysis in coastal zones should assess energy potential, environmental impact, cost, infrastructure feasibility, and reliability, considering geographic variations and deployment needs. While solar energy faces intermittency, wave energy offers more consistent availability. However, the study is limited by resource variability and challenges in scaling infrastructure in coastal environments.

A Photovoltaic (PV) system is selected for solar energy due to its high efficiency, reliability, scalability, and minimal environmental impact, making it ideal for diverse applications. Among PV options, Monocrystalline solar panels are chosen for their superior efficiency (20% and up), power capacity, and durability [12]. While they come with a higher initial cost, they outperform Polycrystalline and Thin-film panels in terms of energy production, space efficiency, and heat tolerance, offering a long lifespan and reliability in various environmental conditions. This combination makes Monocrystalline panels the most effective solution for sustainable solar energy generation. The U-OWC shown in Figure 1 is chosen for wave energy due to its proven reliability, cost-effectiveness, and high efficiency (40-50%), compared to the conventional OWC's 26% [13].

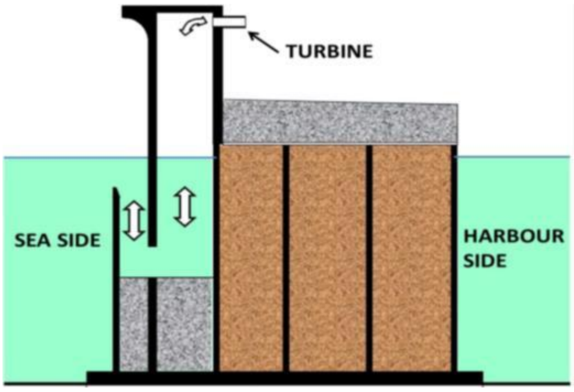

Figure 1: U-OWC Cross-section [13].

The U-OWC performs well in various wave conditions, including the Mediterranean's moderate to strong waves, benefiting from existing breakwater infrastructure to reduce initial costs. Other devices are excluded due to higher maintenance costs and lower efficiency. The U-OWC provides a solid foundation for optimizing renewable energy solutions and supporting future research in sustainable systems. This study uses HOMER Pro and MATLAB for modeling and analysis, as shown in Figure 2. The process starts with site selection and data collection on solar irradiance and wave characteristics. HOMER Pro is used to optimize energy systems, providing key economic indicators such as LCOE, NPC, and greenhouse gas reduction. Known for its robust capabilities in optimizing hybrid solar energy systems, HOMER Pro evaluates the feasibility and cost-effectiveness of solar projects, accounting for solar variability and system configurations [14]. MATLAB models wave dynamics and estimates wave power using empirical formulas. Its flexibility in handling complex simulations makes it ideal for developing customized wave energy models based on wave height, period, and direction, essential for wave energy optimization [15]. The performance of both systems is assessed based on site conditions, and their environmental impacts are evaluated.

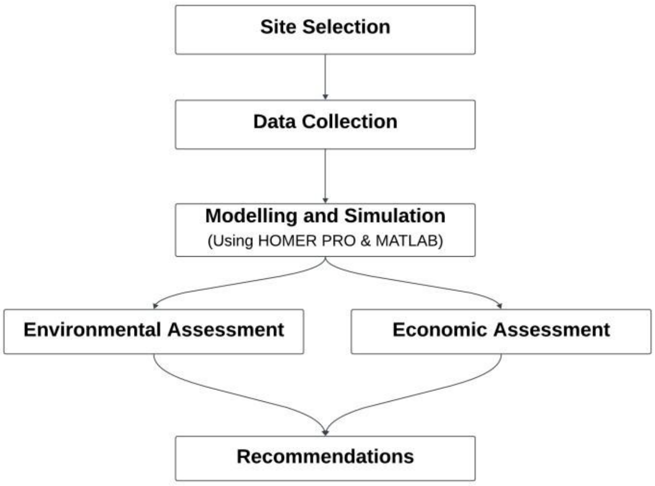

Figure 2: Study methodology

The study methodology presented in Figure 2 examines two key aspects: economic assessment and environmental evaluation. The economic assessment focuses on LCOE, capital, and operational costs, while the environmental evaluation emphasizes the reduction of greenhouse gas emissions, providing insights into the ecological benefits of the energy systems. By considering both LCOE and emissions reduction, this study offers a comprehensive understanding of the overall cost of electricity generation and its environmental impact. Greenhouse gas emissions serve as a critical indicator of a technology's environmental footprint, aligning with global sustainability objectives. To quantify the carbon dioxide reduction resulting from decreased electricity consumption, the Greenhouse Gas Equivalencies Calculator by the U.S. Environmental Protection Agency (EPA) will be utilized.

4. CASE STUDY AND DATA COLLECTION

Alexandria, Egypt's second-largest city and the largest on the Mediterranean coast, accounts for 30.9% of the nation's manufacturing output. Its strategic location offers access to wave energy, while its sunny climate is ideal for solar power. As the population and industrial activities grow, Alexandria faces rising energy demands, making renewable energy key to resilience. The Alexandria Port, handling 60% of Egypt's foreign trade, spans 6.8 km² of water and 1.6 km² of land, with 204,000 m² for customs operations [16]. The ongoing development of Quay wall 55, a multi-purpose terminal consuming 216,000 kWh/day, shown in Figure 3, will serve as a case study to enhance Alexandria's renewable energy capacity.

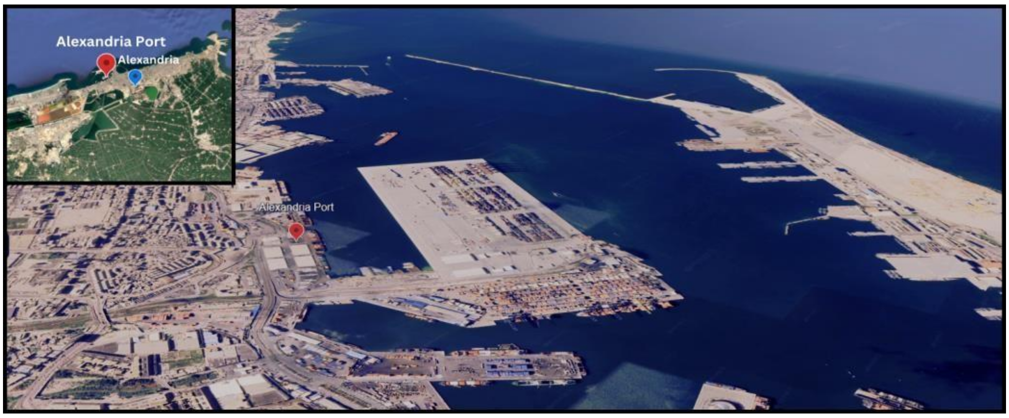

Figure 3: Alexandria Port Lay-out, Alexandria, Egypt. **Source:** Google Earth.

4.1 Solar Energy Potential

In this study, photovoltaic (PV) solar panel installations are considered as a potential source of renewable energy, particularly in locations with ample sunlight. Building rooftops, especially in port areas with adjacent warehouse spaces, present significant potential for rooftop electricity generation, as most existing roofs can support the additional weight of PV panels without requiring structural reinforcement. The proposed solar park layout includes several spaces, such as Warehouse 27A (4,730 m²), Warehouse 27B (5,509 m²), parking areas (3,385.5 m²), a maintenance area (2,590 m²), and an intrusive inspection area in Warehouse 27 (15,400 m²), as shown in Figure 4.

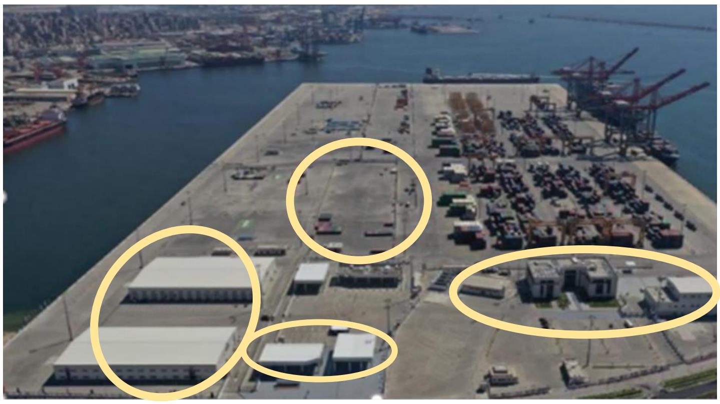

Figure 4: Proposed Intrusive inspection area warehouse [16].

Monocrystalline PV panels, specifically the JINKO Solar JKM465M-7RL3-V model, are selected for their high efficiency (20.71%) and competitive market price. Each panel has a power output of 465 W, with a derating factor of 85% and an expected lifespan of 25 years. The cost is $1210 per kilowatt, excluding mobilization costs. To maximize energy production, the panels' placement and orientation are critical, with an optimal tilt angle of 31.20°, based on the geographical latitude of Alexandria, ensuring maximum sunlight exposure for efficient energy generation. The port's energy demand is primarily electricity (216,000 kWh daily), used for activities like ship-to-shore cranes, refrigerated containers, and lighting. The port terminals, especially the cranes and reefer containers, consume 80% of the energy, while the remaining 20% is used by lighting, workshops, and ancillary buildings. Three solar energy integration scenarios are considered for the port's energy mix:

• **Scenario 1:** Uses PV panels alongside the national grid.

• **Scenario 2:** Includes PV panels, the national grid, and a diesel generator.

• **Scenario 3:** Incorporates PV panels, the national grid, a diesel generator, and storage batteries.

Each scenario will be evaluated based on system components, cost comparisons, and emissions, and compared to the base case, which relies solely on electricity from the grid. The goal is to identify the most effective and sustainable energy configuration for the port, aiming for long-term sustainability.

4.2 Wave Energy Potential

This case study assesses the potential for harnessing wave energy at Alexandria Harbor (31.1680° N, 29.8471° E), where the water depths range from 5 to 7 meters, and the prevailing wave directions come from the northwest (22.5° - 45°). The significant wave height is 1.5 meters, and the peak period is 5.27 seconds, based on data provided by the Coastal Research Institute (CORI) in Alexandria. These parameters were calculated using the methods outlined by Goda (2010) [17] for significant wave height and through spectral analysis following the procedures of Battjes and Janssen (1978) [18] for determining the peak period. A U-Shaped Oscillating Water Column (OWC) system is proposed for deployment at the harbor's breakwater to optimize wave energy capture, as shown in Figure 5.

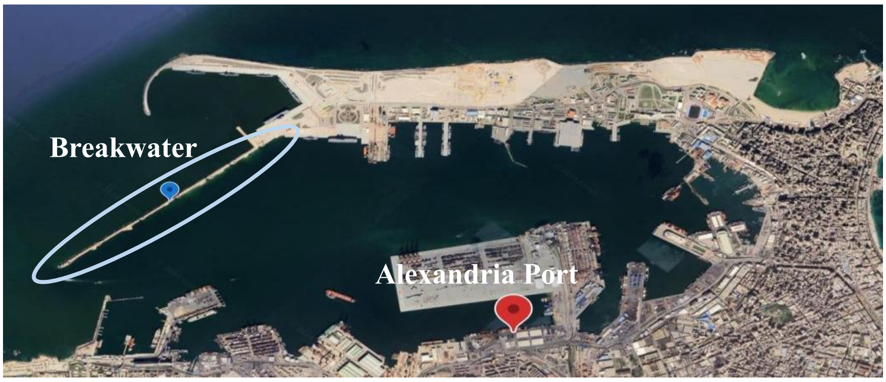

Figure 5: Alexandria Port Breakwater, **Source:** Google Earth.

The potential for harnessing wave energy at Alexandria Harbor has been evaluated by analyzing key wave parameters and applying the Oscillating Water Column (OWC) system. The average wavelength (λ) at the harbor, measured before the breakwater, is derived using the following equation [19]:

$$\lambda=1,56 \,.T_P^2 = 43.33 \ m \quad (1)$$

where:

- λ is the wavelength (m)
- T_P is the peak period (s)

Using the calculated wavelength, the wave speed (v) is determined with the following equation (2) [19]:

$$v=\frac{\lambda}{TP} = 43.33 / 5.27 = 8.22 \ m/sec \quad (2)$$

where:

- v is the wave speed (m/s)

For Alexandria Harbor, the wavelength and wave speed values are 43.33 meters and 8.22 m/s, respectively, which provide the foundational characteristics for evaluating wave energy potential at the site. The average wave power per meter is calculated using the equation [19]:

$$P = \frac{1}{2} \cdot \rho \cdot v \cdot g . A^2 \quad (3)$$

where:

- P is the wave power per meter (W/m)
- ρ is the water density (kg/m³) = 1025 kg/m³
- v is the wave velocity (m/s)
- g is the gravitational acceleration (m/s²) = 9.81 m/s²
- A is the wave amplitude (m), which is the significant wave height

Based on the significant wave height of 1.5 meters, as per the data collected from the Coastal Research Institute (CORI) and calculated [17], the resulting wave power at Alexandria Harbor is approximately 93 kW per meter. The U-Shaped Oscillating Water Column (OWC) system captures wave energy through the pressure difference (ΔP) generated by sea wave movement. This pressure difference transfers both potential and kinetic energy to the air chamber, driving the Wells turbine blades during the intake and outtake cycles. The Wells turbine then converts pneumatic energy into mechanical energy, which is transformed into electrical energy by a Double Feed Induction Generator (DFIG). Known for its high efficiency (40%–70%) and elimination of the gearbox, the DFIG is ideal for handling air pressure fluctuations [19]. The U-OWC system achieves 40%–55% efficiency, significantly surpassing the 26% efficiency of conventional OWCs due to its resonance operation, which maximizes energy absorption and minimizes losses [19]. Table 1 outlines the key dimensions of the OWC device and presents the plant parameters for the Alexandria wave power plant, including the chamber dimensions, turbine specifications, and generator characteristics.

Table 1. Plant Parameters for Alexandria Wave Power Plant [13,19]

Conversion plant	*Parameter type*	*Parameter Calculations*	*Parameter value*
Capture Chamber	*Chamber width (B)*	*(5-6 m)*	*5.5 meters*
	Chamber Length (L)	$= 0.42 \times \lambda$	*17 meters*
	No. of Chambers + 10% Reserved	*Reserved chamber for maintenance*	*106 Chambers*
	Plant span on breakwater	*= B x No. of Chambers*	*583 meters*
Wells turbine	*Water Chamber area (Aw)*	*= B x L*	*91 m²*
	Air chamber Area (A0)	*= Aw * Efficiency of Turbines (0.66%)*	*0.60 m²*
	Turbines mean diameter (D)	$D_t = \sqrt{\frac{4 * A_0}{\pi}}$	*1 meter*
	Number of the blades (n)	*Depending on the Diameter*	*5*
DFIG Generator	*Power rated Prated*	*standardized values*	*80 kW*
	Maximum power Pmax		*100 kW*
	Number of poles		*8*

The U-OWC system operates at resonance, maximizing energy absorption and minimizing losses, achieving an efficiency of 40%–55%, compared to 26% for conventional OWCs [18]. The upgraded U-OWC system, with its higher efficiency compared to conventional OWCs, further enhances energy generation performance. This confirms that Alexandria Harbor has promising wave energy potential, with the U-OWC system providing a sustainable, cost-effective solution for local power generation.

In conclusion, the case study of wave energy at Alexandria Harbor underscores the significant potential for renewable energy, with the U-OWC system offering an efficient method of capturing and converting wave energy into electrical power. These findings support the establishment of a wave energy plant at Alexandria Harbor, contributing to the region's transition to renewable energy sources and enhancing energy security.

5. RESULTS AND DISCUSSION

This section compares solar and wave energy, focusing on their environmental and economic impacts, specifically CO_2 reduction and levelized cost of energy (LCOE). Solar energy offers significant CO_2 reductions and a low LCOE, making it cost-effective. Wave energy, though requiring higher initial investments, provides consistent power generation and substantial environmental benefits. The analysis highlights the trade-offs between these renewable energy options and their potential for sustainable development at Alexandria Harbor.

5.1 Solar Energy Output Analysis

The solar energy output analysis focuses on evaluating the performance, cost, and environmental impact of hybrid renewable energy systems (HRES) at Alexandria Port. This section delves into the

HOMER PRO simulation scenarios and their comparative results to determine the most viable configuration for sustainable energy development.

A. HOMER PRO Simulation Scenarios

In HOMER, optimal system configurations are determined by minimizing total net present cost while adhering to user-defined constraints. This involves selecting and sizing system components such as PV arrays, generators, batteries, and converters, as well as defining a dispatch strategy. Decision variables encompass sizing PV arrays, generators, and batteries, along with managing grid interactions for buying and selling electricity.

This study evaluates three hybrid renewable energy system (HRES) scenarios for Alexandria Port, analyzing component configurations, costs, and emissions:

1. **Scenario 1**: Utilizes 173,251 kW of JINKO Solar PV panels and the national grid, achieving the lowest LCOE of $0.01165/kWh and an NPC of $341.89M. It reduces over 26 million kg of CO_2 annually a payback period of 25 years.
2. **Scenario 2**: Adds a 19,000-kW diesel generator to PV panels and the grid, increasing the LCOE to $0.01473/kWh and the NPC to $432.19M, with capital costs rising to $241M, and the payback period slightly extends.
3. **Scenario 3**: Incorporates battery storage, increasing energy output to 395.73M kWh with 189,639 kW of PV panels. The LCOE is $0.01425/kWh, NPC is $427.57M, and capital costs reach $261.43M.

The analysis highlights the trade-offs between cost, energy production, and emissions reduction across scenarios, with hybrid systems demonstrating strong potential for meeting Alexandria's growing energy demands while providing significant environmental benefits. This comparison serves as a guide for sustainable energy development at the port.

B. Comparison Between Scenarios

As shown in Table 2, the analysis of three HRES scenarios identifies the first configuration as the most cost-effective and sustainable. Utilizing 173,251 kW of JINKO Solar JKM465M-7RL3-V monocrystalline PV panels, a converter, and grid integration, this setup achieves the lowest LCOE at $0.01165/kWh, with a net present cost of $342M and a capital cost of $232M. It offers a 24.5-year payback period. In comparison, the second scenario, incorporating a generator, raises costs to $0.01473/kWh LCOE and $241M capital cost, while the third scenario, with battery storage, results in $0.01425/kWh LCOE and $261M capital cost. The higher costs in the latter scenarios are due to increased operational, maintenance, and replacement expenses, reinforcing the first scenario as the optimal choice.

Table 2. Economic Indicators of the Proposed Scenarios.

Configuration	*NPC ($)*	*Capital cost ($)*	*LCOE ($/kWh)*
1st Scenario	*$342M*	*$232M*	*0.01165 $/kWh*
2nd Scenario	*$432M*	*$241M*	*0.01473 $/kWh*
3rd Scenario	*$428M*	*$261M*	*0.01425 $/kWh*

According to the emission data presented in Table 3 shows that the selected first scenario, utilizing PV modules and grid electricity, achieves significant reductions in emissions compared to the base case, including a decrease of 23,557,152 kg in carbon dioxide, 102,131 kg in sulfur dioxide, and 49,948 kg in nitrogen oxides, demonstrating its environmental benefits.

Table 3. Annual Emissions Comparison Between Base Case and Selected Scenario

Scenario	*Base case*	*Selected 1st scenario*
Carbon dioxide (kg)	*49,826,880*	*26,269,728*
Sulfur Dioxide (kg)	*216,022*	*113,891*
Nitrogen Oxides (kg)	*105,646*	*55,698*

The results of this study align with previous research, demonstrating the feasibility of solar PV systems in ports. Studies on Slovenian and Singaporean ports confirm the cost-effectiveness and emission reductions achieved through renewable energy integration [20,21]. This validates Scenario 1's outcomes, showcasing its sustainability and practicality for Alexandria Port.

5.2 Wave Energy Output Analysis

This section evaluates the feasibility of harnessing wave energy at Alexandria Harbor using an advanced Oscillating Water Column (OWC) system. Wave energy presents a reliable, renewable, and sustainable alternative to fossil fuel-based energy production, utilizing the Mediterranean's dynamic wave activity to generate clean electricity. By examining the technical, economic, and environmental parameters, this analysis demonstrates the viability of integrating wave energy into Alexandria's renewable energy strategy.

A. Wave Energy Power Calculation

The power output per meter of wave crest is calculated as equation (3) [19]:

$$P_{wave} = 0.5 \times 1025 \frac{kg}{m^3} \times 8.22 \frac{m}{s} \times 9.81 \frac{m}{s^2} \times (1.5)^2 = 93\ kW/m$$

This result emphasizes the significant energy potential, with a wave power of 93 kW per meter of wave crest. For a 5.5-meter chamber operating at 40% efficiency with the U-OWC system [19], the power output per chamber reaches 186 kW. To meet the target load of 18 MW, including reserves and maintenance, 106 chambers are required, spanning a total of 583 meters on the breakwater. This demonstrates the scalability and feasibility of wave energy as a reliable and sustainable resource for Alexandria Harbor, positioning it as a strong candidate for renewable energy generation.

B. Feasibility and Cost Analysis

The economic and environmental feasibility of the proposed OWC system is summarized in Table 4. The system features a breakwater of 583 meters and 106 chambers, each producing 186 kW, with a total power capacity of 18,000 kW.

Table 4. Results Summary for Wave Energy at Alexandria Harbor

Wave Energy Performance Overview	
Power Needed	*18,000 kW*
Chamber Width (m)	*5.5 m*
Efficiency of UOWC	*40%*
Power from Wave (kW/m)	*93*
Power By Chamber	*186 kW*
No. of Chamber Needed	*97 Chamber*
Reserved Chamber	*10 Chamber*
Total No. of chamber	*106 Chamber*
NPC ($)	*92,950,153*
LCOE ($/kWh)	*0.0472*
Reduced Carbon Dioxide (CO_2) equivalent (kg/Year)	*55,076,849*

The OWC system effectively meets the power demand of Alexandria Harbor while delivering substantial environmental benefits by reducing CO_2 emissions by approximately 55 million kilograms annually. With an average output of 78 kW per chamber and an efficiency range of 40%-55%, the system demonstrates impressive performance metrics. These findings are consistent with studies by Ramos *et al.*, (2022) [22] and Clemente *et al.*, (2021) [23], which validate the cost-effectiveness and sustainability of wave energy systems in coastal port applications. Such alignment further underscores the viability of implementing the OWC system in Alexandria, offering both economic and environmental advantages.

5.1 Comparison between Solar and Wave Energy Potential

This analysis compares solar and wave energy systems in terms of their environmental and economic impacts for Alexandria Harbor. The findings, summarized in Table 5, highlight the clear trade-offs between the two energy sources:

- **Solar energy** achieves significant CO_2 emission reductions and is economically feasible, with a lower levelized cost of energy (LCOE).
- **Wave energy,** while requiring higher initial investments, delivers greater CO_2 reductions and consistent power generation, offering substantial long-term environmental benefits.

Table 5. The comparison between solar and wave energy.

Metric	***Solar Energy***	***Wave Energy***
Renewable Power Generation (kW)	*18,000*	
Payback Period (years)	*25*	
LCOE ($/kWh)	*0.01165*	*0.0472*
CO_2 Reduction (kg/year)	*26.3M*	*55M*

The comparison presented in Table 5 indicates that solar energy is more cost-effective, with an LCOE of $0.01165 per kWh. In contrast, wave energy has a higher LCOE of $0.0472 per kWh. However, while solar energy reduces CO_2 emissions by 23.5 million kg annually, wave energy provides a significantly greater environmental benefit, reducing emissions by 55 million kg per year. Both energy sources generate 18,000 kW of renewable power.

6. CONCLUSION AND RECOMMENDATIONS

The analysis of solar and wave energy for Alexandria Harbor underscores the strengths and tradeoffs of each energy source. Solar energy is more cost-effective, with a Levelized Cost of Energy (LCOE) of $0.01165 per kWh and an annual CO_2 reduction of 23.5 million kilograms. However, solar power has limitations due to its intermittent nature, producing energy only during daylight hours. This requires energy storage systems, which increase costs and impact the LCOE. Additionally, the limited installation space for solar panels at Alexandria Seaport further restricts its potential. Therefore, solar energy will serve as a partial replacement for the grid and generators at the port, complementing other energy sources, but it cannot fully meet the port's energy demands.

In contrast, Wave energy offers continuous power generation, eliminating the need for storage systems, though its output can decrease during calm wave conditions. This variability emphasizes the need for optimal site selection and system design to ensure reliable performance. The U-OWC system is well-suited for installation on the Alexandria Seaport breakwater, leveraging existing infrastructure. While wave energy provides significant environmental benefits, with CO_2 reductions twice that of solar, its levelized cost of energy (LCOE) remains higher—about four times that of solar—due to higher initial capital costs.

Recommendations:

- **Short-Term Implementation:** Prioritize solar energy (PV systems) for partial replacement of the grid and generators, considering the cost-effectiveness and immediate benefits in CO_2 reduction.
- **Long-Term Planning**: Invest in wave energy as a full replacement for the grid and generators, given its ability to provide consistent, round-the-clock power generation, along with its higher CO_2 reduction potential.
- **Hybrid Approach:** Integrate both solar and wave energy systems to balance cost-effectiveness and environmental sustainability. Solar energy will continue to support the grid, while wave energy will ensure consistent, reliable power.
- **Research and Development:** Continue optimizing wave energy technology to improve efficiency and reduce costs, making it more competitive with other energy sources in the future.
- **Government Authorization:** The Egyptian government holds the authority to determine which renewable energy source is the most optimal for the country, based on national priorities, sustainability goals, and long-term energy strategies. Therefore, the selection of energy technologies must align with the government's overarching vision for Egypt's renewable energy future.

By adopting these strategies, Alexandria Harbor can achieve a sustainable and resilient energy system, leveraging both solar and wave energy to meet growing energy demands while minimizing environmental impact. The Egyptian government's role in guiding this transition ensures that the most appropriate renewable energy mix is chosen for the country's future energy needs.

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