PROJECT 4

MEC ENG 249, Fall 2024 Machine Learning Tools for Modeling Energy Transport and Conversion Process

Title: - Data Analysis of Ocean Energy Potential along the California Coast

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Project Proposal: Data Analysis of Ocean Energy Potential along the California Coast

GROUP MEMBERS: - PARTH PATIL AND MIKIN PATEL

❖ ***Project Title***

➢ *Data Analysis of Ocean Energy Potential across the California Coast*

❖ ***Introduction***

➢ The California coast offers vast potential for renewable energy generation from ocean resources, particularly wave and tidal energy. This project proposes a data-driven approach to assess and analyze ocean energy potential along the California coast using advanced machine learning techniques, including artificial neural networks (ANN). By leveraging key parameters such as wind speed, wave height, and ocean depth, this project aims to identify optimal locations for ocean energy generation, evaluate environmental impacts, and contribute to California's renewable energy strategy.

❖ ***Objectives***

1. Evaluate Ocean Energy Potential: Identify areas along the California coast with high wave and tidal energy generation potential.
2. Site Suitability Analysis: Conduct an analysis of coastal locations based on key parameters to determine optimal sites for energy infrastructure.
3. Predictive Modeling with ANN: Artificial neural networks is used to predict and analyze energy potential based on historical and environmental data.
4. Environmental Impact Assessment: Assess the potential environmental implications of deploying ocean energy infrastructure in selected areas.

❖ ***Methodology***

➢ *Data Collection:* Gather oceanographic data from sources like NOAA and CalWave, focusing on key parameters:
➢ *Wave Height and Mean Wave period:* Measures the energy available from wave forces.
➢ *Water Temperature and Salinity:* This may impact the efficiency of certain energy conversion technologies and potentially have environmental impacts.
➢ *Geospatial Analysis:* Use Geographic Information Systems (GIS) and ECMWF ERA data will be used to set up the spatial map and visualize these parameters along the coastline, identifying clusters of high energy potential. Overlay this information with environmental and socioeconomic data (e.g., marine life habitats, coastal populations) to evaluate impacts.

❖ ***Artificial Neural Network Modeling:***

➢ *Feature Engineering:* Structure data inputs for the ANN, using historical patterns of wave height, wind speed, and tidal variations to train the model.
➢ *Predictive Analysis:* Train an ANN model to predict energy generation potential based on environmental variables, identifying temporal and spatial patterns of energy availability.
➢ *Scenario Testing:* Use the model to simulate how seasonal and climate changes might impact energy production over time, supporting long-term planning.

- *Environmental Impact Assessment:* Conduct an assessment to understand how wave and tidal energy infrastructure might affect coastal and marine ecosystems, including potential disruptions to marine life, habitats, and coastal erosion.

Expected Outcomes

- *Energy Potential Map:* A detailed geospatial map showing areas of the California coast with the highest potential for wave and tidal energy based on analyzed parameters.
- *Site-Specific Analysis Reports:* Reports for each identified site with ANN-based energy predictions, environmental considerations, and potential infrastructure recommendations.
- *Predictive Model Insights:* An ANN model that predicts energy availability under various scenarios, helping stakeholders to understand seasonal fluctuations and plan accordingly.
- *Sustainability Recommendations:* Policy and practice recommendations to guide sustainable ocean energy development with minimal environmental impact.

Applications

- Renewable Energy Expansion: Contribute to California's renewable energy goals by identifying viable clean energy sources.
- Environmental Conservation: Use impact assessments to mitigate risks to marine ecosystems.
- Data-Driven Policy: Support data-backed decision-making for state agencies and coastal communities.

DRIVE LINK FOR PROJECT: -

https://drive.google.com/drive/folders/1ongsJdZgsAFx5M2vs7kjCSgcHFlpYQNu?usp=sharing

INTRODUCTION

California's coastline holds tremendous potential with respect to wave and tidal forms of ocean resource energy, which must be converted to electrical energy. This paper presents a data-intensive approach to carrying out a comprehensive assessment and analysis of ocean energy potentials along the coastline of California, using state-of-the-art machine learning techniques and artificial neural networks. It aims to attain the perfect positions ideal for generating ocean energy using key parameters like the wind speed, wave height, and depth of the ocean. The project will help develop a renewable energy strategy for California while assessing potential environmental impacts. Key objectives include assessment of ocean energy potential for identification of hotspots, carrying out site suitability analysis, using artificial neural networks for predictive modelling, and assessment of the environmental consequences of ocean energy infrastructure deployment.

It also collects data from oceanographic conditions from reputed sources like NOAA and CalWave, considering data on mean wave period and total swell height of the wave over the period. Supported by Geographic Information Systems-GIS and ECMWF ERA5, geospatial analysis will be performed to visualize these parameters to locate high-energy potential clusters. The dataset consists of 3 years of data from 2021 to 2024 with each hourly wave height and wave period. This would cover the novelty of artificial neural network modeling for predictive analytics in feature engineering in structuring data inputs, training the ANN model to predict energy generation potential, and scenario testing in simulating seasonal and climate changes to be considered during energy production. This would also deliver detailed results in forms such as an energy potential map, site-specific analysis reports, predictive model insights, and sustainability recommendations. By combining advanced data analysis techniques with environmental considerations, this project aims to provide valuable insights for expanding California's renewable energy portfolio while ensuring sustainable development of ocean energy resources.

The given market analysis for the ocean wave energy technology reflects a growing industry that is still early years of commercial development. Moreover, due to continuous industry development, research is being considered on several Wave Energy conversion technology such as point absorbers, oscillating wave surge converters and overtopping converters. Companies leading this development include Ocean Power Technologies and CalWave Power Technologies, both of which develop wave energy conversion systems that are promising enormous po ssibilities in this area. Theoretically, the estimated yearly energy potential for waves around U.S. coasts is ~2.64 trillion kilowatt-hours and would correspond to about 63% of the total U.S. utility-scale electricity generation during 2023, making big promises for wave energy in contributing toward the renewable energy landscape.

Nevertheless, the market faces numerous challenges before it experiences wider diffusion. This includes the complex marine conditions that the technologies in service must endure, high capital expenditure in initial investment stages, and cost-effective designs that could competitively and favorably contend with other established energy sources. Currently, the LCOE for point absorbers is still relatively high, though expected to decline with technology maturity and the realization of economies of scale. Besides, the environmental factor has to do with market acceptability and should affect the marine ecosystems minimally to command regulatory and public support. Finally, as much as it sounds promising, ocean wave energy technology will only succeed when barriers to the present day's ongoing investment in research and development are overcome to realize its full potential within the renewable energy sector.

METHODOLOGY

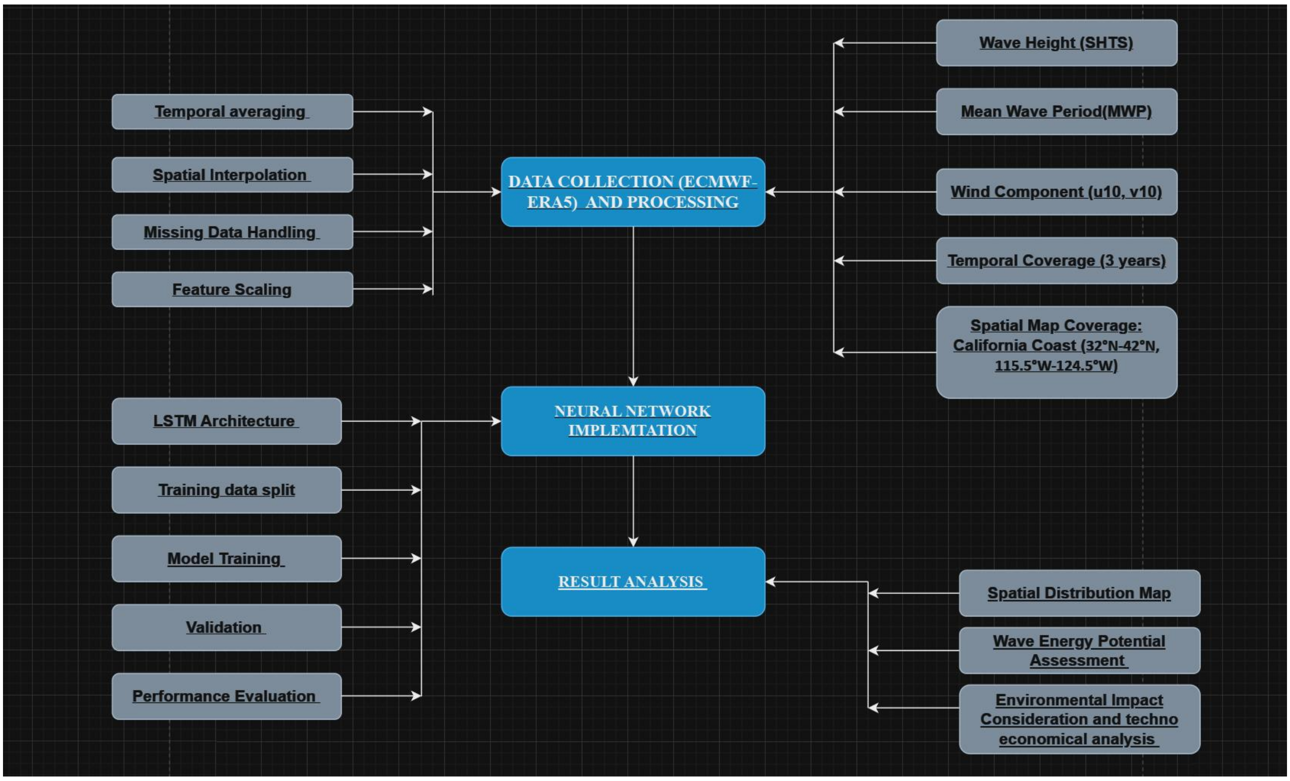


Fig:1 Methodology chart of the Project

❖ *Data Acquisition and Processing*

➢ It begins with the gathering of data from ECMWF ERA datasets, where the most important parameters to extract are the significant wave height (SHTS), mean wave period (MWP), and wind components (u10, v10). The spatial domain is between 32°N-42°N latitude and 115.5°W-124.5°W longitude, while temporally, the three years is considered. The preprocessing steps to be applied to data quality and coherence include Temporal averaging, spatial interpolation, treatment of missing data, and feature scaling.

❖ *Neural Network Implementation*

➢ The implementation uses a modified version of Long Short-Term Memory LSTM for sequential oceanographic data analysis. Further, it covers a step-by-step division of training data, training of the model by optimized parameters, and strict validation processes. Metric designing for performance evaluations is carried out to quantify a model's predictive accuracy and dependability on wave energy potential estimates.

❖ *Result Analysis and Evaluation*

➢ The final step involves a detailed result analysis that is based on three main components, specifically: First, spatial distribution mapping, which shows the potential for wave energy resources in California's coastline; second, a detailed assessment of wave energy potential through the measurement of power generation , at respective locations; and lastly, consideration of environmental impacts and techno-economic evaluation for the practical and viable realization of proposed wave energy developments. This multi-faceted approach helps comprehensively understand the technical potentials and practical implementation challenges.

The formula Used in the Methodology are: -

Wave Energy Formulas:

- *Energy Density Formula*

$$\mathbf{E = 0.0625 * \rho * g * Hs\text{^}2}$$

Where: E = Wave energy density (J/m^2), ρ (rho) = Seawater density (1025 kg/m^3), g = Gravitational acceleration (9.81 m/s^2), Hs = Significant wave height (m)

- *Wave Power Formula*

$$\mathbf{P = 0.49 * \rho * g\text{^}2 * Hs\text{^}2 * (T/(64\pi))}$$

Where: P = Wave power (W/m), T = Mean wave period (s)

- *Carbon Reduction Calculation*

$$\mathbf{Cr = Ea * Fe * \eta g * Fd}$$

Where: Cr = Carbon reduction, Ea = Annual energy production (kWh), Fe = Grid emission factor, ηg = Grid efficiency, Fd = Displacement factor.

- Annual energy production (Ea):

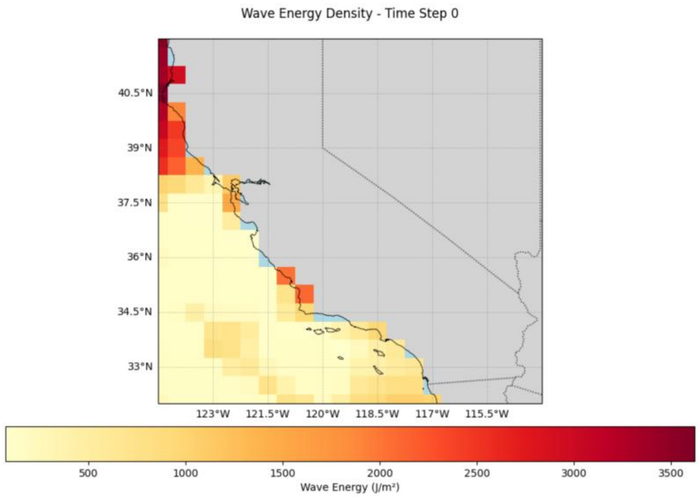
$$\mathbf{Ea = P * 8760}$$

where 8760 represents hours per year.

Parameter Category	**Variable**	**Value**	**Unit**
Environmental	Seawater density (ρ)	1025	kg/m^3
Environmental	Gravitational acceleration (g)	9.81	m/s^2
System Efficiency	Capacity factor	0.33	-
System Efficiency	System efficiency	0.052	-
System Efficiency	Extraction factor	0.0406	-
Grid	Emission factor	0.0408	kg CO_2/kWh
Grid	Grid efficiency	0.95	-
Grid	Displacement factor	0.85	-
Spatial	Total area	13.5×10^9	m^2
Spatial	Grid dimensions	100 × 100	cells

Table:1 Parameters used in analysis

TASK: -1 RESULTS AND ANALYSIS OF THE GRAPHS



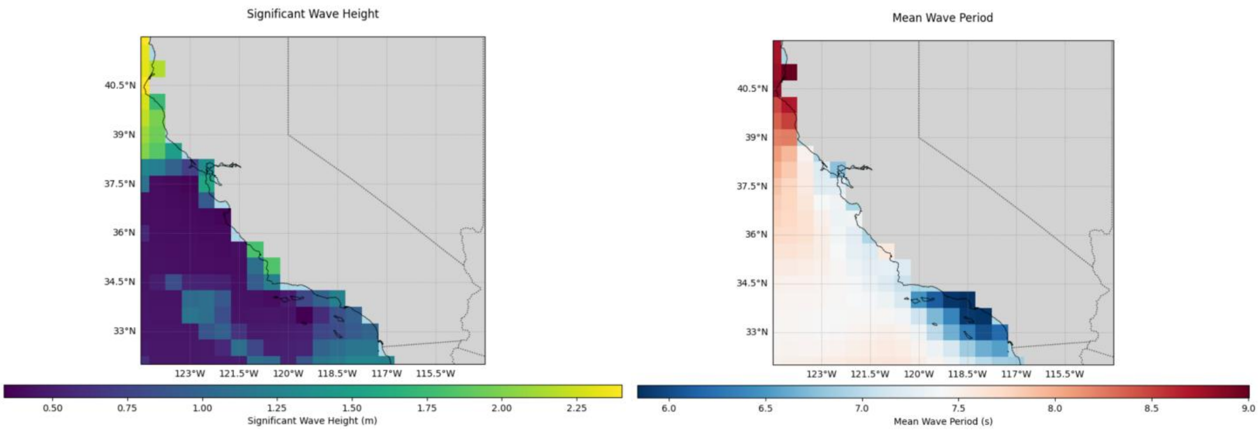


Fig:2 Spatial Map distribution for California Coast for Wave Energy Density, Significant Wave height and Mean Wave Period

These images give a relatively detailed analysis of wave characteristics along the California coast, looking at three primary parameters: Wave Energy Density, Mean Wave Period, and Significant Wave Height. Let us look at them one by one:

- *Wave Energy Density*

➢ The Wave Energy Density map exhibits a strong north-south gradient:
➢ Northern California (North of 40.5°N): Highest energy density with 3000-3500 J/m²
➢ Central California (37.5°N to 40.5°N): Medium energy density, about 1500-2000 J/m²
➢ Southern California (south of 37.5°N): Lower energy density, mostly 500-1000 J/m²
➢ This distribution suggests the north coast has the highest wave energy harvesting potential

- *Average Wave Period*
  - One striking feature apparent in the Mean Wave Period map is:
  - North region: Longer intervals of 8.5-9.0 seconds.
  - Central region: Mid-intervals of 7.0-8.0 seconds.
  - South region: Times between 6.0-7.0 seconds shorter.
  - Notably, there is an area of shorter wave periods (6.0-6.5 seconds) in the southern part of the map, which may be related to the local bathymetry or wind patterns.

- *Significant Wave Height*
  - The Significant Wave Height map shows:
  - Northern California: Highest waves, 2.0-2.25 meters
  - Central California: Moderate wave heights, 1.25-1.75 meters
  - Southern California: Reduced wave heights, 0.50-1.00 meters
  - This distribution of Wave Energy Density is compatible since wave height is an essential factor in determining the energy potential.

❖ ***Comprehensive reasoning: -***

- *Regional Variations:* All three parameters tend to increase steadily towards the north, decreasing towards the south. This would imply that the most favourable conditions for wave energy conversion are found in northern California.

- *Correlation:* There is a strong correlation between wave height, period, and energy density. Areas with high wave heights and long periods correspond with areas of high energy density.

- *Influence of Bathymetry:* Features observed in the Mean Wave Period map indicate that local bathymetric features contribute to forming wave characteristics along the coastline.

- *Seasonal Considerations:* The above maps represent a single temporal snapshot. It is important to recognize that wave conditions can vary seasonally; therefore, a thorough analysis requires data obtained over multiple periods.

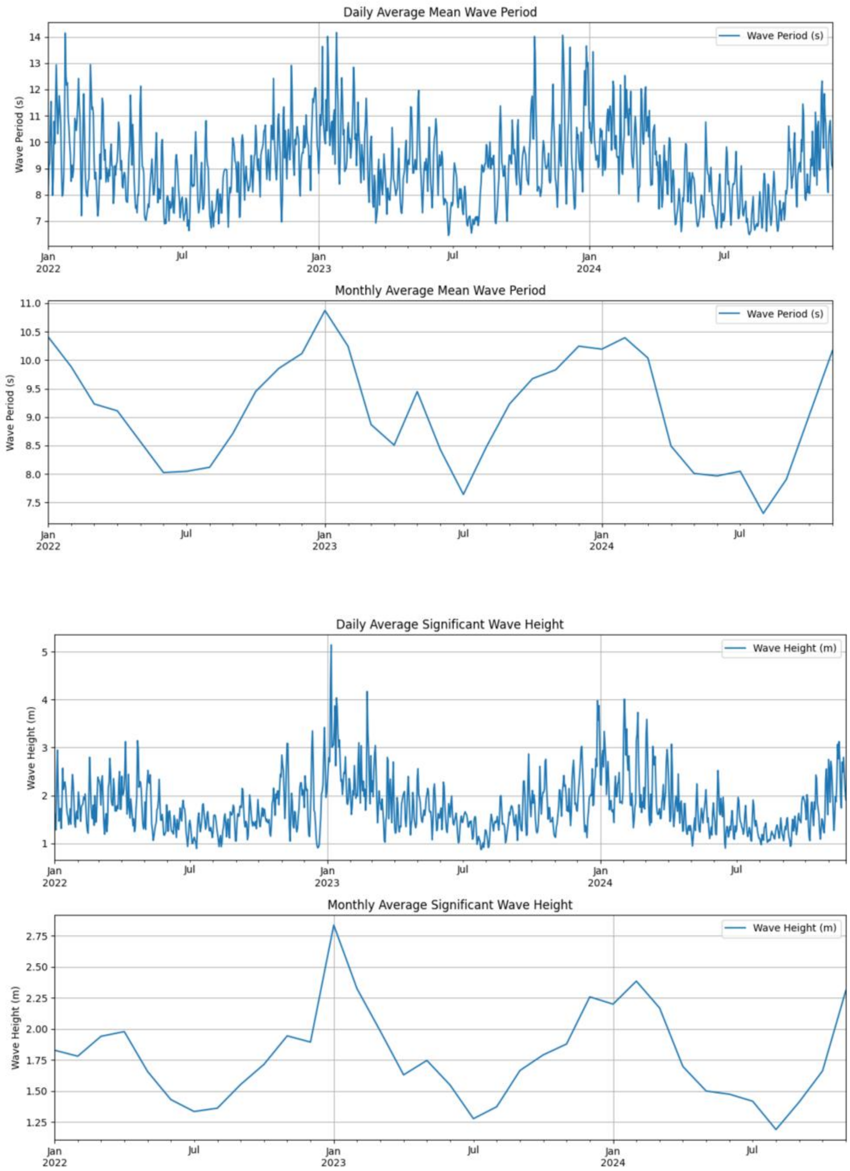
- *Implications for Wave Energy:* The northern coast, mainly north of 39°N, appears most promising for wave energy harvesting regarding high energy density, long wave periods, and considerable wave heights.

This analysis provides important information about potential locations for wave energy projects, highlighting the northern coast of California as the most favourable area for development and indicating that the entire coast has some level of wave energy potential.

Region Used (%)	Power Generation (TWh/year)	Carbon Reduction (million metric tons CO2/year)
100	140.7	4.614.59
50	70.04	2,307.30
40	56.03	1,845.84
30	42.02	1,384.38
20	28.01	922.92
10	14.01	461.46

Table 2 showing the power generation potential and carbon emission reduction for different percentages of the California coast used for wave energy conversion

The Table:2 shows that the power generation potential and carbon emission reduction increase linearly with the percentage of the California coastline utilized for wave energy conversion. However, it must be realized that the carbon reduction estimates are probably on the high side and may not reflect realistic numbers when considering California's current energy mix and grid emissions parameters.



<u>Fig: 3 Time Series Analysis for Mean Wave Period and Wave Height (Daily and Monthly analysis)</u>

- ***<u>Temporal analysis of wave period and wave height variability around the Californian coastline from January 2022 to December 2024</u>***

- The analysis provides interesting seasonal and other variations of interest regarding wave energy resource assessment. Data here, at average daily and monthly levels, provide an insight into short-term variability and longer general tendencies. Daily averages for wave periods vary within a factor of about 7 to 14 seconds; there is considerable seasonality. Winter months consistently have higher wave periods, often exceeding 13 s. Day-to-day variability is extensive, with changes of 2 or 3 s quite common. Monthly averages-even out these fluctuations range between about 7.5 and 11 s. This point of view captures the seasonality of the trend, peaking during the winter months and depressing during the summer period. Precisely, Janu ary 2023 and 2024 recorded the maximum monthly averages of about 10.9 and 10.4 seconds, with the minimum for July and August of both years being around 8 seconds.

- Wave height data presents similar seasonal trends but with higher variability. The daily average of the significantt wave height varies from 1 to 5 meters, with the biggest waves during winter. This dataset presents many high-energy events, including the remarkable peak of 5 meters in January 2023. Day-to-day changes of 1-2 meters are common and reflect inherently dynamic characteristics of wave conditions. Monthly values range from 1.25 to 2.75 meters, emphasizing winter peaks and summer troughs. January 2023 had the highest monthly value of about 2.8 meters, while January 2024 had an approximate value of 2.4 meters. Summer months, especially July-August, have consistently recorded the lowest wave heights, averaging approximately 1.3-1.4 meters.

- This analysis underlines pronounced seasonality in both wave period and significant wave height, pointing out a distinct relationship between the parameters. Some interannual variability can also be detected from these data, with the peaks in 2022-2023 higher than in 2023-2024. This is a serious concern concerning design and implementation in wave energy utilization, with highly energetic winter and summer conditions, which were stable but of much lower energy. The extreme events recorded are highly relevant for assessing the maximum possible and operational risks of wave energy converters deployed along the coast of California.

Some Geographical Factors that affect this analysis:

- Geographical features strongly influence the pattern of waves and their time evolution along coastline of California. Some important key factors that determine the analysis of wave dynamics include:

- *Coastal Topography*

- California's shoreline encompasses many topographical features that will affect wave behavior.

- Coast Range: This mountain range is situated along the coast from the Oregon border, well past the northern edge of the Los Angeles Basin, primarily within 50 miles of the shore. Such sudden rise directly from the ocean to heights of several thousands of feet affects wind and wave generation.

- San Francisco Bay: This major break in the Coast Range lets abundant marine air penetrate inland; it has regional wave and weather effects.

- *Bathymetry:* The underwater topography of the continental shelf significantly impacts wave characteristics:

- Continental Shelf Width: Variations in shelf width along the coast affect how waves propagate and dissipate energy as they approach the shore.

- Submarine Canyons: Features like the Monterey Canyon and La Jolla Canyon create large spatial gradients of wave energy along the coast

- *Latitudinal Gradient:* The tremendous north-south length of the shoreline of California 1,200 causes a massive difference in latitude:

  - Northern California: Larger waves and stronger storms occur there than to the south. Winter extremes are, on average, 6.3 m to the north and 2.0 m to the south.

  - Southern California: The area south of Point Conception has a significantly reduced wave resource due to the blocking effect of the Channel Islands.

- *Offshore Islands:* The presence of offshore islands, particularly in Southern California, affects wave patterns:

  - Channel Islands: These islands block much of the wave energy from the northwest, resulting in a reduced wave resource in the Southern California nearshore areas.

  - Tanner and Cortez Banks: Located west of the outer islands, these areas have unblocked and energetic wave climates despite being in Southern California

- *Coastal Orientation.* Wave exposure changes with the orientation of the coastline relative to predominant wave directions:

  - Northwest-facing Coasts: These are more open to the prevailing westerly and northwesterly swells, especially in Northern and Central California.

  - South-facing Coasts: Better protected in Southern California from the dominant northwest swells but more open to southern hemisphere swells.

These are all fundamental geographical elements contributing to the complicated and varied wave patterns along the coast of California, both in terms of historical assessment and future forecasts of changes in wave height due to climate change.

TASK: -2 TECHNO-ECONOMICAL ANALYSIS

Currently, ocean wave energy technology is not widely used on a commercial scale. The industry is still in its early stages of development, with most projects being in the research, development, and testing phases. However, there are several promising technologies and ongoing projects that are advancing the field of wave energy conversion. Here is an overview of some key aspects of ocean wave energy technology:

- ***Several Wave Energy Conversion Technologies are currently being developed and tested:***

- **Point Absorbers:** These are floating buoys that absorb energy from the movement of waves at the water's surface. Ocean Power Technologies (OPT) is a leading company in this area, developing their PowerBuoy system.

- **Oscillating Wave Surge Converters:** These devices are mounted on the seabed in shallower water and harness wave energy with an oscillating flap. AW-Energy's WaveRoller technology is an example of this type.

- **Oscillating Water Columns:** These are partially submerged, hollow structures open to seawater below the surface. As waves rise and fall, air is pushed through a turbine to generate power.

- **Overtopping Converters:** These devices capture water from waves to drive turbines, like hydroelectric dams.

- *Current Projects and Companies:* While not yet widely used, several companies are at the forefront of wave energy technology development:

- CalWave Power Technologies: In 2021, CalWave deployed its xWave prototype off the coast of San Diego, California, for a six-month trial.
- CorPower Ocean: This Swedish company is developing a Wave Energy Converter (WEC) that uses a buoyant structure to capture wave energy.
- Carnegie Clean Energy: An Australian company developing the CETO® technology, which uses submerged buoys to capture wave energy.
- Eco Wave Power: This Israeli company attaches floaters to existing structures like breakwaters or piers to capture wave energy.

- *Potential and Challenges:* Wave energy has significant potential:

- The theoretical annual energy potential of waves off the U.S. coasts is estimated to be as much as 2.64 trillion kilowatt-hours, equal to about 63% of total U.S. utility-scale electricity generation in 2023.
- Wave power is more consistent and predictable than some other renewable energy sources, being 2060 times more energy-dense.

- *However, the technology faces challenges:*

- Surviving harsh ocean environments and extreme weather conditions.
- Developing cost-effective and efficient designs to compete with other energy sources.
- Overcoming technical hurdles to move from prototype stage to commercial deployment.

While ocean wave energy technology shows great promise, it is still in the early stages of development. Continued research, investment, and testing are needed before it can be widely deployed and contribute significantly to the global energy mix.

❖ ***Point Absorbers Market Fit***

- ➢ Ocean wave energy technology, particularly **point absorbers**, is an emerging renewable energy source with promising potential. Here is a detailed breakdown of the costs associated with point absorbers off the coast of California:

- ➢ Capital Expenditure (CapEx): The initial capital cost for point absorbers can vary significantly based on the scale of the project. For a commercial-scale installation:

- ➢ A 10 MW array of point absorbers is estimated to have a CapEx of approximately $98 million.

❖ *This cost includes:*

- Device structural components
- Power Take-Off (PTO) system
- Mooring and foundation
- Electrical infrastructure
- Installation

- ➢ The device structure and PTO system typically account for the largest portions of the CapEx, often comprising up to 40% of the total initial costs.

❖ *Installation Charges*

- ➢ Installation costs for point absorbers are substantial due to the offshore nature of the technology. These costs can range from 15% to 20% of the total project cost. For a 10 MW array, this translates to approximately $14.7 million to $19.6 million.

❖ *Installation involves:*

- Marine operations for device deployment
- Mooring system installation
- Electrical cable laying
- Use of specialized vessels and equipment

❖ *Operation and Maintenance (O&M) Charges*

- ➢ Annual O&M costs for point absorbers are estimated to be around $3.9 million for a 10 MW array. This includes:

1. Routine maintenance
2. Repairs and replacements
3. Environmental monitoring
4. Insurance

- ➢ O&M costs can be significant due to the harsh marine environment and the need for specialized vessels for maintenance operations.

❖ *Levelized Cost of Energy (LCOE)*

➢ The LCOE for point absorbers varies based on the scale of deployment:

- Single unit: $2.69/kWh
- 10-unit array: $0.79/kWh
- 50-unit array: $0.43/kWh
- 100-unit array: $0.36/kWh

For a 10 MW commercial-scale array, the LCOE is estimated at $0.98/kWh. This relatively high LCOE compared to other renewable sources is due to:
1. The early stage of technology development
2. High initial capital costs
3. Challenging marine environment for operations

❖ *Cost Reduction Potential*

➢ The LCOE for point absorbers is expected to decrease as the technology matures:

1. Moving from a single-unit deployment to a 10-unit deployment can reduce LCOE by 65-80%.
2. Further cost reductions are anticipated through:
   - Improved device performance
   - Economies of scale in manufacturing
   - Optimized installation and O&M procedures

❖ *Return on Investment (ROI)*

Based on the information provided in the search results and some hypothetical estimations, here is a Return on Investment (ROI) table for a Point Absorber Wave Energy Converter over a 15-year period:

Year	Total Investment ($)	Total Net Revenue ($)	Cumulative ROI (%)
0	98,000,000	0	-100
1	101,900,000	3,500,000	-96.57
2	105,800,000	7,000,000	-93.38
3	109,700,000	10,500,000	-90.43
4	113,600,000	14,000,000	-87.68
5	117,500,000	17,500,000	-85.11
6	121,400,000	21,000,000	-82.7
7	125,300,000	24,500,000	-80.45
8	129,200,000	28,000,000	-78.33
9	133,100,000	31,500,000	-76.33
10	137,000,000	35,000,000	-74.45
11	140,900,000	38,500,000	-72.68
12	144,800,000	42,000,000	-71
13	148,700,000	45,500,000	-69.4
14	152,600,000	49,000,000	-67.89
15	156,500,000	52,500,000	-66.45

Table:3 ROI Analysis for the Ocean Energy

This table is built on the following key assumptions:
1. Initial Capital Expenditure (CapEx): ***$98 million*** for a ***10 MW*** array of point absorbers.
2. Annual Operation and Maintenance (O&M) Costs: $3.9 million.
3. Annual Net Revenue: ***$3.5 million***, based on estimated energy production and the current high Levelized Cost of Energy (LCOE) for wave energy.
4. Total Investment: Includes the initial ***CapEx*** and cumulative ***O&M*** costs.
5. Total Net Revenue: Represents cumulative revenue over the analyzed period.
6. Cumulative ROI: Calculated as:

$$(\textbf{Total Net Revenue} - \textbf{Total Investment}) / \textbf{Total Investment} \times \mathbf{100)}$$

The ROI analysis reveals a negative return over the 15-year timeframe, emphasizing the current challenges of wave energy technologies. These challenges include high initial costs and relatively low energy production compared to more mature renewable energy sources. However, as technology advances and costs decline, the ROI is expected to improve significantly in the future.

The negative ROI also highlights why wave energy remains in the research and development phase, with most projects operating as pilot or demonstration initiatives rather than full commercial deployments. For example, within the 15-year analysis, the cumulative ROI for point absorber wave energy converters remains negative at -66.45%, emphasizing the need for further technological and economic advancements.

❖ *Key Factors Contributing to Negative ROI:*

1. High Initial Capital Costs (CapEx): The upfront investment required for wave energy converters is substantial.
2. Significant Ongoing O&M Costs: Marine environments demand rigorous maintenance, adding to operational expenses.
3. Relatively Low Energy Production: Wave energy systems currently lag other renewable technologies in terms of efficiency.
4. High LCOE: The cost of energy produced by wave energy systems remains uncompetitive with other renewables.

❖ *Pathways to Improve ROI:*

➢ To achieve positive returns, several advancements and cost reductions are necessary, including:

1. Enhanced device performance and energy conversion efficiency.
2. Economies of scale in manufacturing and deployment.
3. Optimization of installation and O&M processes.
4. Improved durability to withstand harsh marine conditions.

Although the current outlook shows a negative ROI, wave energy technology is still in its early stages. Continued research, development, and commercial-scale deployments are expected to drive down costs and enhance the economic viability of point absorber wave energy converters. With these advancements, wave energy has the potential to play a significant role in the renewable energy mix.

CONCLUSION

This ocean energy study along the coast of California accentuates some strong potential in wave energy resources. Equipped with innovative machine learning techniques, artificial neural networks allow our work to show how integrating data-driven findings with environmental and Geo-considerations forms a prerequisite for identifying high potential areas. It included a detailed study of wave energy density variability with the parameters of wave height, mean wave period, and wind components. The northern part of California proved to be the most favorable region due to its high wave energy density and extended wave periods, which are suitable for potential energy-harnessing projects.

Though very promising, wave energy technology is still in its infancy due to economic and technical problems. High capital costs, combined with the demanding marine conditions and the relatively high LCOE, limit its competitiveness compared to other renewable sources. However, the potential of the industry to reduce costs through technological innovation, economies of scale, and efficiency improvements does indeed offer a pathway to broader adoption. The barriers that stand in the way will require sustained efforts in research and development, combined with pilot projects and support by regulatory schemes, as this study has illustrated. Mitigation of environmental impacts and public and stakeholder engagement will also be important to make deployment sustainable.

Ocean wave energy has the potential to add diversity and strength to California's renewable portfolio, meaningfully addressing the goal of reducing carbon emissions. Insights gained fr om this study provide a proper framing from which improvements for future projects could be drawn. As ongoing innovation is pursued with stakeholders, wave energy has the potential to develop into competitive constituent positions within a global transition of energy toward broader susta inability goals of climate change mitigation.

While not directly related to costs, it is worth noting that point absorbers have shown minimal environmental impact. A third-party assessment for a pilot project off the coast of San Diego concluded that the technology would have no adverse effect on marine life in terms of entanglement, sound, collision, electromagnetic fields, and discharges.

In conclusion, while the current costs for point absorber wave energy technology are high, there is significant potential for cost reduction as the industry scales up and matures. The technology's environmental friendliness and the abundant wave resources off the California coast make it a promising avenue for future renewable energy development.

Some Recommendation which our group felt needs to be implemented for improvement of ocean wave energy: -

Sustainability Recommendations: Policy and Practice for Ocean Energy Development

1. Environmental Impact Assessments: Site-specific assessments to mitigate any effects on marine ecosystems and ensure ongoing environmental monitoring.
2. Eco-Friendly Technology: Prioritize innovative, low-impact designs such as point absorbers and oscillating water columns, incentivized through R&D grants.
3. Strategic Site Selection: Apply GIS to identify areas with higher energy while trying to avoid areas of Marine Protected Areas and sensitive habitats.
4. Community Engagement: Engage local stakeholders, Indigenous groups, and communities at the very early stages to make sure decisions are transparent and benefits are equitably distributed.
5. Sustainable Operations: Plan maintenance out of peak migration or breeding seasons to minimize disturbances underwater.

6. Integration of Carbon Reduction: Include the adoption of marine energy within California's grid to accomplish net-zero emission goals.
7. Monitoring and Adaptive Management: Create programs for long-term monitoring regarding cumulative impacts and unforeseen challenges.
8. Policy Coordination: Coordinate across the energy, environmental, and fisheries sectors to align goals and reduce conflict.
9. Economic Support: Tax incentives, subsidies, and funding for pilot projects to help reduce costs and scale up commercialization.
10. Global Collaboration: Learn from international leaders such as Scotland and Portugal, adopt best practices, and be in line with global sustainability goals.

By doing so, California can develop ocean energy in a sustainable way, preserve its marine ecosystems, and further its leadership with renewable energy.

Work Distribution: -

Mikin Patel: Completed the techno-economic analysis, including the calculation of ROI, and drafted the entire write-up for this section.

Parth Patil: Conducted the temporal analysis and assessed wave energy potential, including calculations for different area usages, and prepared the complete write-up for this section.

Collaborative Efforts: Both Mikin and Parth jointly worked on code generation, testing, modifications, and analysis.