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ITDECC_049

A COMPREHENSIVE SURVEY ON ADVANCED TECHNOLOGIES FOR ENHANCING EFFICIENCY IN OCEAN ENERGY HARVESTING

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ABSTRACT

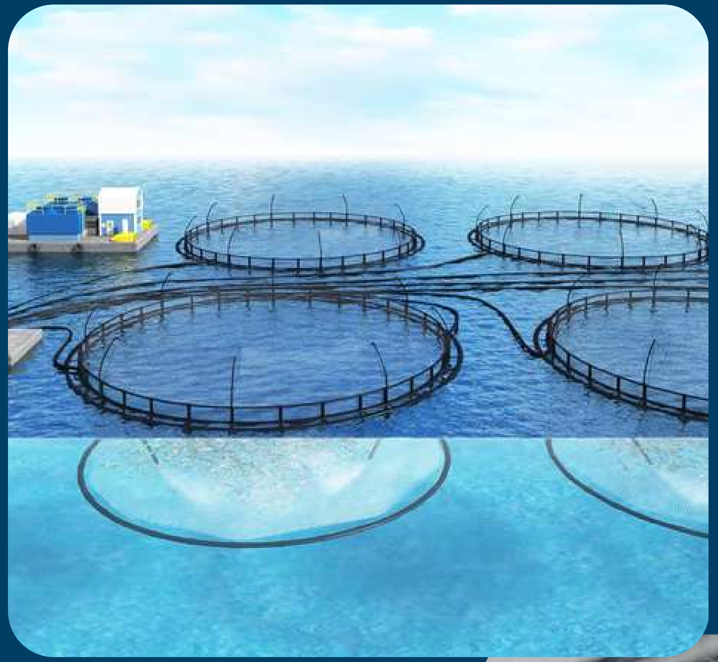
Ocean energy like tides, waves, and thermal gradients offers vast potential for a zero-carbon future and supports UN Sustainable Goal 7 (Clean Energy). While challenges like variability and integration exist, advances in IoT, AI, and nanoelectronics enable smarter, more reliable energy harvesting. Emerging nanogenerators and intelligent systems pave the way for sustainable ocean energy solutions worldwide.

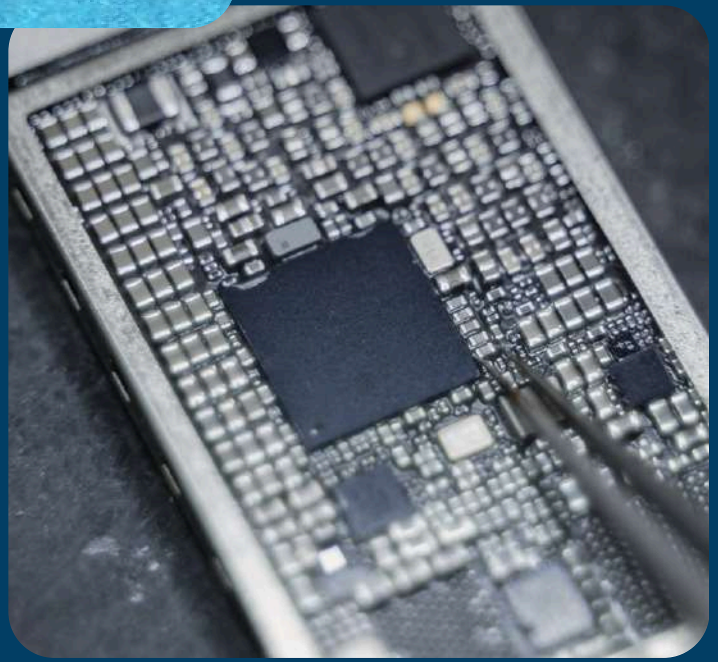
INTRODUCTION

Ocean energy from waves, tides, and currents is a clean and sustainable source that can cut carbon emissions. Though challenges like variability and grid integration remain, new tools such as IoT, AI, and IoUT improve efficiency and reliability. With its vast 7,500 km coastline, India has huge potential for ocean energy, making it a key player in future renewable power.

NANO TECHNOLOGY

According to recent research nanogenerators uses movement/heat/light into electricity. This method uses small materials with certain properties that help to capture and use energy. Piezoelectric harvesters use vibrations and turn them into electricity i.e. they become independent of battery sources. they can be very useful in electricity generation at remote places.





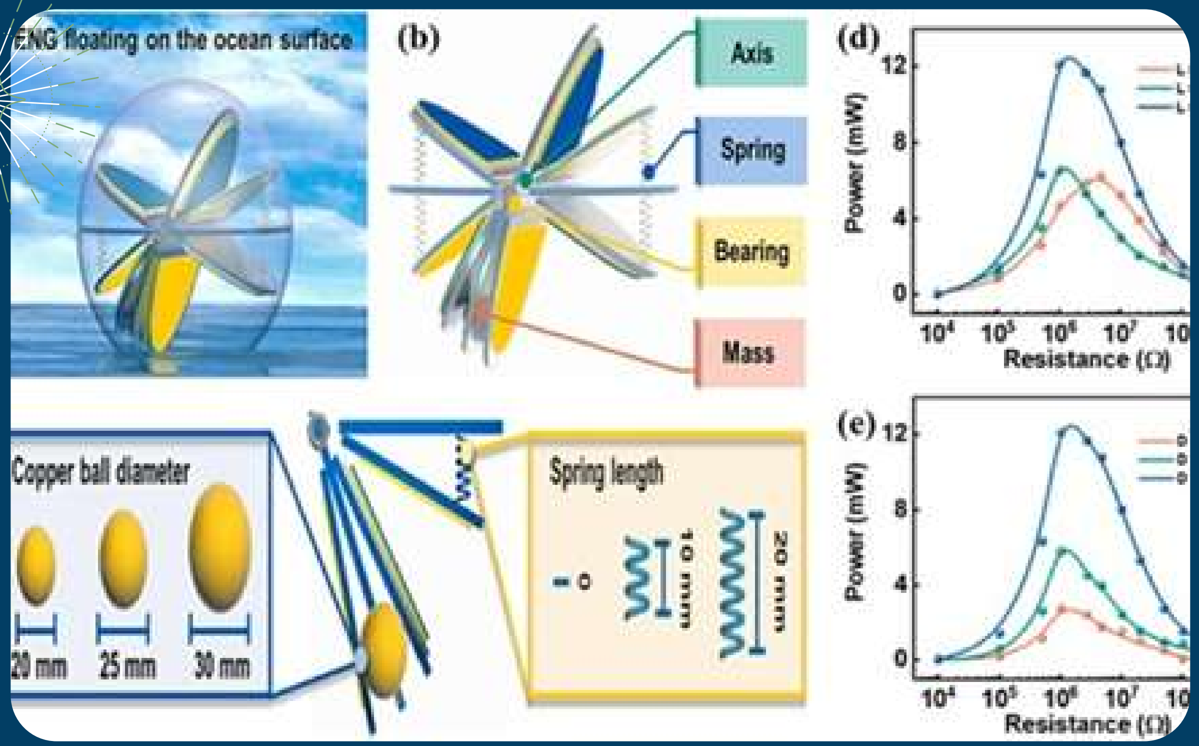
TRIBOELECTRIC NANOGENERATORS

Principle: Triboelectrification + Electrostatic induction

Pros: Low-cost, simple, compact, lightweight, fast, eco-friendly, efficient at low freq

Designs: Spring-assisted, biomimetic (flower/duck), wave-energy harvesters

Advances: Thin-film collectors, vortex-to-electric conversion (resonant state)



AI- POWERED DIGITAL TWIN OF THE OCEAN FOR WAVE ENERGY PREDICTION:

Principle: Machine learning (LSTM) trained on historical ocean data for wave forecasting

Pros: Accurate, data-driven, adaptive, real-time predictive capability

Design: Multi-LSTM models validated using OWC system in Jeju, South Korea

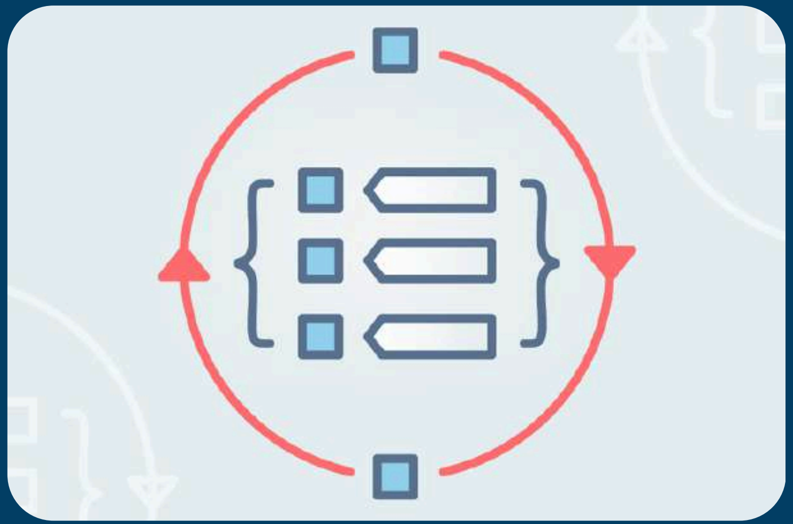
Advances: Digital twin integration, AI-enhanced forecasting, autonomous ocean energy optimization

Fig. Oscillating Water Column system, Jeju South Korea

WEC OPTIMIZATION

01. Motion Detection

02.Data Processing



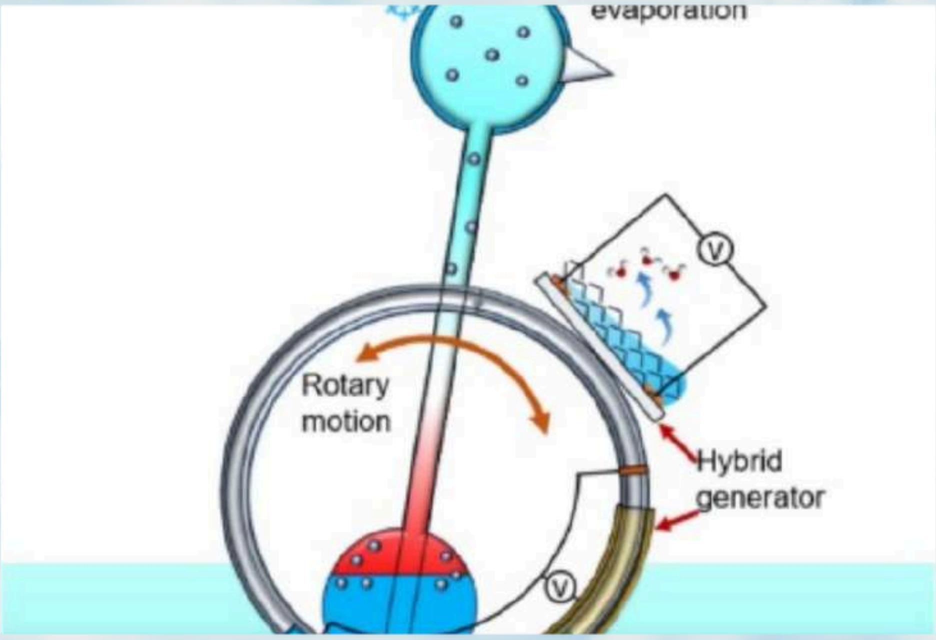
03.AI Integration

04.Decision Making

HYDROVOLATIC GENERATORS

The generators propel water through its nanochannels through the process of evaporation, converting ambient heat to electricity.

These are environment friendly and include biomimetic interfacial evaporation-driven generators inspired by lotus plants, flexible two-mode electric nanogenerators for dynamically changing aqueous solutions and ion selective hydrogel films.



WAVE HEIGHT PREDICTION IN OCEAN ENERGY

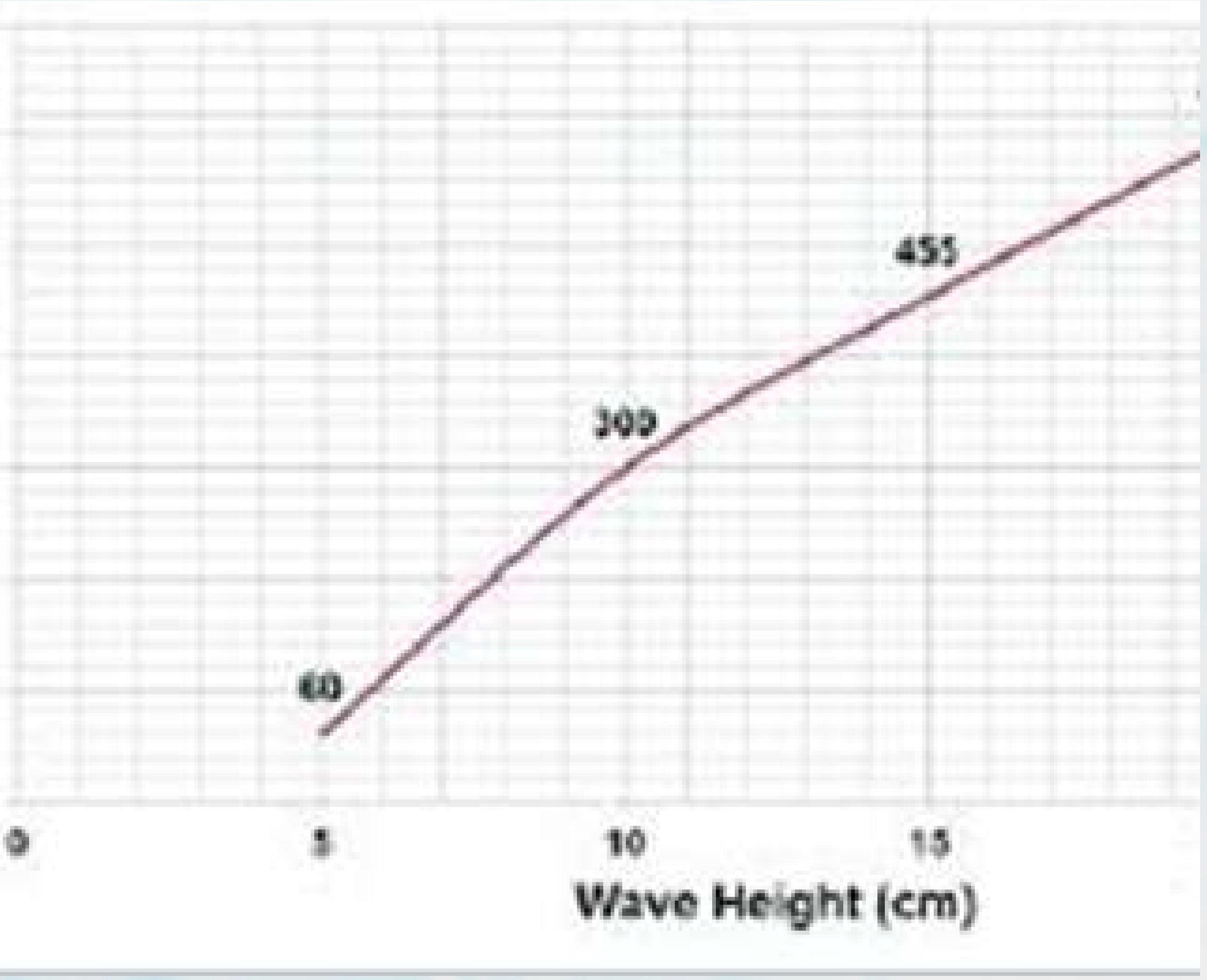
- Ocean energy systems face two major challenges: **low energy density** and **changing wave conditions.**
- Researchers have proposed a **real-time wave height prediction model** based on an LSTM-DE architecture.
- With uncertainty calibration (STD scaling), it ensures both high **predictive accuracy** and r**eliable operation**, making ocean wave energy harvesting safer and more efficient. (D. Lee et al, 2025)

REINFORCEMENT LEARNING FOR OCEAN WAVE CONVERTERS

- Energy capture from waves often depends on the **difference between crests and troughs.**
- By combining **wave simulations with Deep Reinforcement Learning (DRL)**, researchers optimize the interaction with Ocean Wave Surge Converters (OWSCs).

- The approach remains **effective under wave height variations.** Interestingly, the optimization effect becomes more pronounced with longer wave periods, highlighting new directions for **efficient energy harvesting.** (A. Barua et al., 2024)

ENABLING IOT THROUGH INTERMITTENT COMPUTING



- Future Energy-Harvesting IoT devices (EH-IoT) require techniques that can adapt to **fluctuating energy availability.**

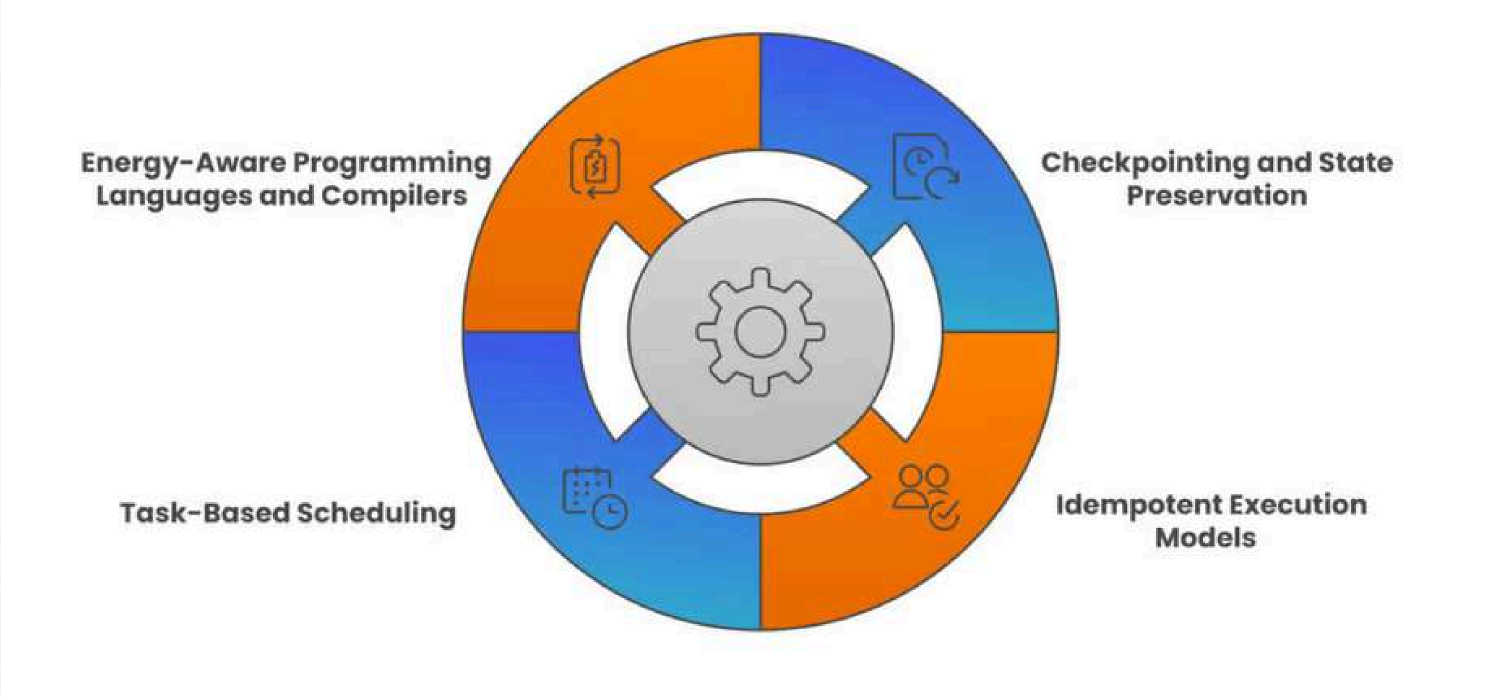
- **Deep learning methods** allow devices to balance precision with computation cost, supported by runtime energy input prediction.

- Unlike traditional systems that rely on continuous power, intermittent computing enables devices to **pause and save progress during power loss**, ideal for sustainable IoT. (V. Kortbeek et al, 2020)

INTERMITTENT COMPUTING

- ocean energy such as waves and tides is unpredictable. Intermittent computing is used to operate such power sources. Instead of completely shutting down and restarting, the system stores its progress and resumes where it left off once power is back.
- systems make use of energy storage solutions like capacitors, supercapacitors, or small batteries to hold the energy they collect.
- They use state saving and task management techniques, which allows the device to resume the process without any hassles.
- Hardware and software units are optimized to make use of minimum energy; therefore, maximum use can be made from limited resources.

- Despite all these research, there are still multiple limitations such as
  Capacitors and supercapacitors can store only very little power while input sources are highly unpredictable so it is really inefficient
- limited non-volatile storage can lead to data loss or corruption during power failures.
- On the software side, development remains complex, with specialized frameworks and a lack of standard programming models making it harder to scale or port applications



CONCLUSION

Ocean energy harvesting is a sustainable method of power extracting from tides, waves etc. Our survey compares different harvesting methods based on factors such as efficiency, voltage, and power density and provides an evidence-based insight from years of documented research.

While triboelectric harvesters face sustainability concerns, piezoelectric systems have limited practical applications, and electromagnetic designs remain bulky, ongoing advancements continue to drive rapid progress in wave energy harvesting technologies due to the vast potential of ocean resources.

ENERGY HARVESTING TECHNOLOGIES – KEY PARAMETERS

Parameter	PENG	EMG	TENG	DEG	Hydrovoltaic	Hybrid
Output Voltage	2.6 V (±1.3 V); up to 36.93 V	7.2 V (open-circuit)	60 V	–	0.16–0.72 V	–
Output Current	–	21.2 mA (short-circuit)	60 μA	–	1.2–60 μA	–
Output Power	29.7 μW (<2 Hz); 5 mW; 16.72 mW	520 mW (ultra-low freq); 120 mW; 80.87 mW	10 mW (rolling ball)	0.87–3.8 W	0.048 μW	21.95 mW
Energy Density	2.11 W/m^2	–	>100 W/m^3; 5.38 W/m^3	140 mJ/g	–	5.73 W/m^3 to 100s W/m^3
Power Density	–	0.3 W; 3453.8 kg/m^3; 0.36 mW/cm^3	5.38 W/m^3; >100 W/m^3	–	45.6 $\mu W/cm^2$	5.73 W/m^3 to 100s W/m^3
Efficiency	Enhanced via up-conversion & magnetic augmentation	–	–	18%	–	–
Special Features	Frequency up-conversion, magnetic augmentation, vortex flow	Halbach array, tunable stiffness	Rolling ball, spherical arrays	Wave-cycle harvesting	Nanomaterial-water interaction	Multi-mechanism integration

Thank You!