nature portfolio

Peer Review File

A Pendulum-based Nanogenerator for High-Entropy Wave Energy Harvesting

Corresponding Author: Professor yong Ma

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This manuscript presents an innovative distributed marine monitoring system based on a chaotic-pendulum wave energy harvesting buoy, incorporating a triboelectric-electromagnetic hybrid nanogenerator. The study addresses critical challenges in deep-sea unmanned monitoring systems, such as endurance, reliability, and effective wave energy capture under harsh marine conditions. The work demonstrates significant scientific value and practical potential, particularly in improving wave energy utilization efficiency and buoy stability. The manuscript is generally well-structured, and the technical descriptions are detailed and clear. The manuscript presents a significant advancement in wave energy harvesting and its application to distributed marine monitoring. With minor revisions to address the points raised above, it will be suitable for publication in Nature Communications.
1. While the manuscript highlights the effectiveness of the chaotic pendulum and hybrid nanogenerator, further emphasis is needed on how the proposed system advances beyond existing wave energy harvesting technologies. For example, the advantages of the chaotic pendulum proposed in this paper and the reasons why it is suitable for monitoring buoys are not sufficiently explained. Please elaborate further.
2. The authors are suggested to provide additional details about the controlled water tank and open-sea trial setups, including specific environmental conditions (e.g., wave height, frequency) to better contextualize the reported results.
3. Please discuss the scalability of the system for larger deployments and any potential limitations (e.g., durability of materials, long-term performance in corrosive environments).
4. While the manuscript is generally well-written, a few sentences could benefit from minor grammatical adjustments for improved readability (e.g., "maintaining buoy equilibrium in marine environments" could be rephrased for clarity).
5. Please ensure tense consistency throughout the text, making sure that all verbs are in the same tense, especially when describing experiments and results, where the past tense is usually used.
6. TENG and EMG should be used in full when they first appear in the abstract.
7. The PCB in Fig. 1b should belong to the TENG module.
8. The symbols in the formulas throughout the text should be consistent, for example, the top and bottom of Eq. 1-1 “d·σ” and “εrε0”, and the symbols “×” and “·”, etc. should be formatted consistently.
9. In the numerical simulations, the selection process for the material parameters and the source of the tool library are not explained. The author should include these details along with proper reference citations. Besides, please pay attention to the citation of equations in the article.

Reviewer #2

(Remarks to the Author)
Overview and general recommendation:
The paper proposes a chaotic pendulum triboelectric-electromagnetic hybrid nanogenerator-based wave energy converter (CP-TEWEC) for marine equipment powering applications. The mechanism seeks to hybridize a rotary double-pendulum TENG with a standard EMG, in order to promote operational synergies and enhance energy harvesting from low frequency, low amplitude ocean wave action. An experimental study was conducted to demonstrate the proposed device, namely for supplying a self-powered marine temperature and humidity sensing system.
The Abstract is concise, yet informative and clear. The English grammar and structure require punctual improvements. The Introduction could benefit from some expansion and contextualization with regards to existing literature, as well as with

regards to the work's motivation, objectives and contributions to reducing knowledge-gaps. This only becomes clearer near the end of the paper. The supplementary material was very useful and highly appreciated.
The paper is quite interesting and the findings pertinent, particularly the tank testing and sea trials. The CP-TEWEC concept is disruptive, but there are some matters that require clarification. For now, considering this and my comments, I recommend that the paper be subjected to major revisions. Even so, I encourage the authors to address the comments, which I hope will be helpful to them and, if adequately revised, should result in my approval for publication.
2.1. Major comments:
1- Line 34: reference 6 regards a case study of seawater electrolysis, and it is unclear how it corroborates the statements you make beforehand on autonomous IT systems (control units, sensors, etc.) at sea. I would recommend changing it (perhaps you could use one of the preceding references instead, in order to also mitigate reference lumping from Line 31);
2- Line 38: the resource can vary in time and space (for instance, there are even "hot-spots" of wave energy around the world), though it is always present at greater or lower magnitude. Though it is relatively predictable, abundant and broadly distributed, I would recommend you also highlight its greater density when comparing wave energy with wind and solar, for example, instead of mentioning the "site-independent exploitation";
3- Line 43: in the reference you cite they specify the "low efficiency of the EMG under irregular and low-frequency (< 5 Hz) ocean waves, the equipment manufacturing and maintenance costs are extremely high". There is also a discussion on the devices' environmental sustainability, corrosion resilience and other topics. Perhaps you could highlight some of these to better contextualize the limitations of EMGs. I would also recommend discussing, briefly, non-EMG alternatives (aside from TENGs, naturally) and their limitations, in parallel to what you do for EMGs. Alternatively, you could better explain why you give emphasis to EMGs within the scope of WEC technology. I understand they will be considered further along the paper, but EMGs should be better introduced at this point, in order for the reader to understand why they are mentioned in detriment of non-EMG options. I also felt that the contextualization was a bit generic. It would be more interesting to see some more discussion on existing literature (e.g., "Author X studied TENGs in a buoy for Y purpose, from which they obtained Z results", "Authors A and B used a novel TENG configuration to power a C device, at sea", etc.) in the Introduction, as well as a schematic or better summary of the triboelectrification and electrostatic induction processes in TENGs;
4- Lines 46-48: you should address some additional disadvantages/limitations of existing TENG technologies (e.g., as done briefly in Line 57), which can also help you elaborate on the motivation for your work and its contribution towards the current state-of-the-art. You should also be mindful of the sentence that starts in Line 48, as it gives the impression that the TENGs reported in the three references you provide were all tested at sea (which is not the case, if I understood correctly – they were mainly subjected to laboratory demonstration);
5- Line 50: this is a pertinent development, but it should be better explained how the EMGs and TENGs complement one another and how they can be integrated into an effective hybrid system. On the latter, you could develop a bit more on some works found in literature. For example, there are relatively recent studies in which TENGs are even incorporated into EMG-based WECs, such as Salter's Duck, E-Motions, etc. Note also that, when you state that the hybridization promotes "broadening the operational bandwidth of WECs", you should be mindful that i) the power output of EMGs and TENGs can be quite distinct, in terms of magnitude, ii) WECs operate optimally under resonance, and while TENGs can provide novel motion response "peaks" that can be explored, promoting resonance is usually achieved through natural frequency tuning, latching and other types of control mechanisms (so the wave period/frequency would matter as well, extending from what you discuss in Line 62), and iii) as stated in line 60, in some instances, TENGs can "mitigate the wave-induced motion response, functioning in a manner akin to a tuned mass damper". On point iii), the reference you provide even states that "Tuned mass dampers (TMDs) are effective in a small range around the resonance frequency, and they are sensitive to the working conditions";
6- Line 68: while I understand some of the advantages of the hybridization, won´t the matter of mass distribution and its influence on the floater response remain unresolved (or possibly worsened)? Also, since you are proposing a double-pendulum with a chaotic behavior, and given the stochastic nature of waves, won´t this affect the predictability and stability of the power output? The perspective of decoupling the system from the floater's dynamic response is interesting, but the power regularization process doesn´t seem sufficiently evident to me, at this stage. Perhaps a supporting Figure or description could make it clearer (or referring earlier to Figure 1);
7- Line 79: how do these values pair up against other case studies found in literature? It would be interesting to have said comparison, in order to see how well your device fairs against others. I think this was your goal with Figure 4h, but it would be helpful to have, at least, a brief mention here of that comparison. Furthermore, when you state that there is a "4.6-fold increase in the generator's energy storage capacity", what is the reference to which you are comparing it with? You could also discuss the difference in the individual EMG and TENG's performance from the hybrid system;
8- Figure 1g: the significant wave height values are in model (reduced-) scale or prototype (full-) scale? Also, why did you consider these specific Hs and Tp values? Are these the representative conditions of your case study region?;
9- Check if all the parameters of Equations 1- were defined in the text. Can you also please clarify the differences between your Equation 1-4 and the one presented in reference 60, Equation 3b, as well as the definition of the force term (adhesion versus attraction)? Prior to Figure 2, you should have mentioned that the simulations were undertaken with COMSOL and detail a bit more how they were setup, in order to promote reproducibility. It would be equally pertinent, for validation and uncertainty analysis purposes, to have a better perception of the correlation between the expected values from the mathematical formulas versus those of the COMSOL simulations, since you only provide a single voltage value reference (430 versus 466.67 V);
10- Line 220: could you please elaborate a bit more on these promising outcomes with the inclusion of the CEC? Also, note that your sentence in Line 226 hints at a beneficial operational overlap of the TENG and EMG, as they compensate each other in terms of operational range. There might also be a typo here, as I believe you wanted to write "19 mW" or "0.19 W". It is also strange to see the 10 mW value for the TENG, as the maximum average power seems to be closer to 20 mW (at least, visually): Could you also put Figure 3f and h with the same range for the average and peak power values, please? Lastly, could you also clarify what was the amplitude of the rotations?;
11- Line 272: likely you have resonance occurring at that period of about 1.9 s, as it matches the peak from the FFT analysis

and the free decay test intervals. It is curious to see such a regular free decay pattern from the device, as I would expect a more complex pattern, given its double-pendulum and chaotic nature. Regarding the numerical versus experimental tests, could you please clarify a bit better the testing conditions? Most of the results you provide refer to a single wave height value, but here you compare multiple values. Did you conduct tests with only one irregular wave case or with different wave conditions?;
12- Figure 5: did you conduct tests to verify humidity, temperature and other factors that can affect the EMG and TENG's operational efficiency at sea?; Did you consider extreme events and survivability testing?;
13- Line 314: note that, for operational purposes, you should consider that, at sea, you have variable wave height, period and direction, which can affect the performance of your device over time. It might also be more pertinent to design the device's resonant frequency to match the most energetic wave conditions at the deployment site, which are not necessarily the average ones. You should also consider how this can affect the floater's stability: a WEC usually seeks larger motions to extract energy, but this can be counterproductive for floating structures and systems who are sensitive to sudden and large motions. Also, it should be clearer to the reader when you are transitioning from the tank tests to the sea trials. I would advise including a connecting paragraph and/or splitting it into two sub-sections. Lastly, did you notice whether the wind was an important or negligible factor in the device's performance?;
14- Line 419: you had already mentioned the dimensions of the wave tank. Did you evaluate potential wall effects and re-reflections off the tank boundaries affecting your measurements? Did you compare the generated waves with those actually intended to make (calibration procedures)? Also, do you reckon that wave directionality can impact your device's performance or not, based on the wave tank experiments? Was the sampling rate of 1 kHz the same for all the measurement systems? Lastly, were you able to measure the floater motions in real time with the electrometers?

2.2. Minor comments:
1- You might want to consider alternative or additional keywords to better showcase the scope and content of your paper;
2- Avoid lumping of references, as done in Line 31, 36 or 40, among others. In the case of Line 40, the number of references is very high, and I believe the paper would benefit from a summarized description of existing case studies related to said references. 3 references should be provided at once, maximum, in order to corroborate your statement;
3- Some minor English grammar errors were detected. Please double-check the paper and correct them, accordingly;
4- Line 44: instead of "wave energy harvesters", you can simply use the abbreviation WECs;
5- Line 56: eliminate or reduce considerably? Please confirm what you mean;
6- Line 63: aside from avoiding reference lumping, I think some of the references are not specific to rotary pendulum-type TENGs. Hence, you should consider removing them;
7- The resolution of Figure 1, in particular the letters, should be slightly enhanced for clearer reading;
8- Please check if you have a typo (hollow box) in Equations N2-5 and -6. Verify also if Equations N2-1 and -2 are correctly written, as they seem slightly different from the reference I usually resort to for verification (Handbook of Ocean Wave Energy, page 56). In page 59 of this document, you should also verify the definition of the ratios between Tp and Te, which you designate as a "shape" parameter in N2-7. Confirm also if what you are defining in Equation N2-8 is the Capture Width Ratio metric (CWR) commonly used in WEC design;
9- Line 146: could you clarify the reason for this outcome of the magnetic flux intensity? A similar clarification would be appreciated with regards to Line 181's remark, by comparison with what is discussed in reference 60 after Equation 2c;
10- Figures and Tables should appear right after they are first cited in the text (for instance, correct this in Figure 3);
11- Table S1: were these values measured in the physical model of the device, or obtained under the specific condition of a maximum static friction force of 3.5 N? Please clarify, as well, whether you are working with model or prototype values, particularly when you define parameters such as the rotating pendulum's weight;
12- Please check if Figure S4 has a correct caption, as in both a) and b) you present current and charge results. If I interpreted it correctly, b) is a zoom of a), but please confirm;
13- Line 354: could you please clarify if the 24 sectors account for all of the outer diameter of the device (7º times 24º is equal to 168º, under 360º, and 52.5 times 7º converted to radians is equal to about 154 mm, slightly above 150 mm)? Also, in Line 393, did you use a specific type of commercial buoy as a reference to define your model, or was the model constructed without a specific reference?

Reviewer #3

(Remarks to the Author)
This study presents a chaotic-pendulum wave energy harvesting buoy based on a triboelectric-electromagnetic hybrid nanogenerator. The chaotic pendulum decouples the floater-generator motion, converting irregular wave energy into steady power and maintaining buoy equilibrium in marine environments. This work can be useful for small scale ocean energy harvesting, I recommended this paper for major revision.
environments.
1. What are the primary advantages of this work compared to state-of-the-art small-scale wave energy converters utilizing conventional electromagnetic generators (EMGs)?
2. What is the total energy conversion efficiency of the proposed system, from wave energy to electricity? How does this efficiency compare with state-of-the-art hybrid TENG systems or small-scale wave energy converters using conventional EMGs?
3. Given that hybrid systems have greater complexity than standalone TENG systems, which increases the risk of system failure, how does this design address potential reliability issues?
4. How does the output power of the LTC3588 circuit compare when using only an EMG versus a hybrid configuration combining TENG and EMG? Specifically, is there a significant power loss in the energy management process when the outputs of TENG and EMG are combined without impedance matching?

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors addressed all the comments raised by the reviewers. So I recommend the paper to be accepted by Nature Communications.

Reviewer #2

(Remarks to the Author)
The paper proposes a chaotic pendulum triboelectric-electromagnetic hybrid nanogenerator-based wave energy converter (CP-TEWEC) for marine equipment powering applications. The mechanism seeks to hybridize a rotary double-pendulum TENG with a standard EMG, in order to promote operational synergies and enhance energy harvesting from low frequency, low amplitude ocean wave action. An experimental study was conducted to demonstrate the proposed device, namely for supplying a self-powered marine temperature and humidity sensing system.

The authors underwent significant efforts towards improving the paper, based on the reviewrs' comments. This is highly appreciated and has been reflected upon the enhancement of the work's quality. On my part, I am willing to recommend an acceptance of the paper in general. However, I would like the authors to explain a bit better their responses to my Major Comments #8 and #11. My doubts relate to the wave conditions and the scale of the wave flume experiments:
i) the authors state that the scale of the experiment was 1:1, but in the wave flume the wave conditions seem to refer to values at a reduced scale. While the buoy itself may conserve its full-scale size, the wave conditions should also be equivalent to those at sea. Either both are at reduced scale or full-scale, but not a combination of either. The duration of the experiments with irregular waves also seems limited, as I am used to seeing works with 512 or more waves being generated per cycle for an adequate sweep of the wave spectrum;
ii) the authors should clarify better what are the local wave conditions and what is the original dataset from which the data was extracted. A wave rose or historical time series Figure would assist in this matter, for instance.

Reviewer #3

(Remarks to the Author)
authors answer all my comments. I recommend this paper for publication

Responses to Editor and Reviewers

Manuscript number: No. NCOMMS-24-75130

Title: Self-Powered Marine Monitoring: A Chaotic Pendulum Hybrid Nanogenerator for High-Entropy Wave Energy Harvesting

Authors: Tiancong Zhao[1,2,3], Zhengyu Li[1,3], Bo Niu[1,3], Guangci Xie[1], Liang Shangguan[1], Meikun Zhang[1], Yurun Zhu[1], Yong Ma[*1,3], Chao Hu[*1] and Ying Li[*2]

Thank you very much for considering our manuscript for possible publication in Nano energy. We really appreciate that the reviewers read our manuscript carefully, and giving us insightful comments and suggestions. We have read and considered the comments and suggestions from the reviewers carefully, which are indeed very helpful in making the paper more solid and convincing. We have revised the original manuscript accordingly, and come up with a point-to-point response to the reviewer's comments. All the revisions are highlighted in the revised manuscript. I hope that the revised manuscript is accepted for publication in Nature communications.

In this document, we quote in green words from the referees' reports. Our replies follow in black words after "**Response**". The modifications in the revised paper are highlighted in red. Detailed answers to the reviewers' comments and explanations of the corrections in the revised version of the manuscript are given as follows. Once again, we thank the editor and reviewers for your constructive feedback!

Reviewer #1 (Remarks to the Author):

This manuscript presents an innovative distributed marine monitoring system based on a chaotic-pendulum wave energy harvesting buoy, incorporating a triboelectric-electromagnetic hybrid nanogenerator. The study addresses critical challenges in deep-sea unmanned monitoring systems, such as endurance, reliability, and effective wave energy capture under harsh marine conditions. The work demonstrates significant scientific value and practical potential, particularly in improving wave energy utilization efficiency and buoy stability. The manuscript is generally well-structured, and the technical descriptions are detailed and clear. The manuscript presents a significant advancement in wave energy harvesting and its application to distributed marine monitoring. With minor revisions to address the points raised above, it will be suitable for publication in Nature Communications.

1. While the manuscript highlights the effectiveness of the chaotic pendulum and hybrid nanogenerator, further emphasis is needed on how the proposed system advances beyond existing wave energy harvesting technologies. For example, the advantages of the chaotic pendulum proposed in this paper and the reasons why it is suitable for monitoring buoys are not sufficiently explained. Please elaborate further.

Author response: Thank you very much for raising this concern.

The miniaturization, unmanned operation, and automation of marine monitoring buoys have emerged as key developmental trends in oceanographic observation technology. This evolution simultaneously imposes stricter requirements on WECs regarding compact dimensions, operational stability, and power generation efficiency. When implementing miniaturization designs for WECs, two critical challenges emerge: Firstly, the detrimental effects of wave impacts and related factors on the device become significantly amplified. Secondly, the mass proportion of the power take-off system relative to the entire device structure increases substantially. These combined aspects compromise both operational reliability and long-term durability. A comparative analysis of performance characteristics for existing small-scale wave energy converters is presented in Table 1.

Table 1. Advantages and disadvantages of different converting mechanisms.
Note: “+” means it agrees well, “-” means it disagrees, and “○” means ordinary.

Type		Stability	Low cost	Reliability	Adaptability	Compactness	High output
Spring mass		-	+	○	-	-	○
Gyroscope		+	-	○	+	○	-
Pendu-lum	Horizontal axis	-	+	-	○	-	-
	Vertical axis/ Inclined axis	-	○	-	○	-	○
	Parallel/ Series	-	○	-	○	-	○
	Chaotic	+	○	+	+	+	+

In comparison, the compact CP-TEWEC proposed in this study, based on a rotational pendulum mechanism, demonstrates distinct advantages through its innovative design.

First, the incorporation of a tray pendulum structure effectively maintains the system’s center of gravity during rotational motion, resolving the eccentric mass distribution issue inherent in miniaturized rotational pendulum devices. This ensures both compact dimensions and enhanced operational stability, providing marine sensors with a reliable power supply environment.

Second, the integration of rotational power generation components within the tray structure significantly optimizes spatial utilization. The hybrid TENG-EMG energy harvesting system achieves superior power output density compared to conventional configurations.

Third, the system combines the pendulum’s sensitivity to low-frequency waves with TENG’s efficient low-frequency energy conversion capabilities, while the EMG component effectively harnesses high-frequency wave energy, collectively extending the operational bandwidth.

Finally, the chaotic pendulum mechanism is characterized by its simple and compact structure, which enables economical and efficient large-scale production and distributed deployment, which fully meets the requirements of modern ocean monitoring buoys.

2. The authors are suggested to provide additional details about the controlled water tank and open-sea trial setups, including specific environmental conditions (e.g., wave height, frequency) to better contextualize the reported results.

Author response:

We appreciate the reviewer's attention to the details of the water tank and open-sea trials. To further enhance the clarity of the paper, we have supplemented and emphasized these descriptions in the revised manuscript. We sincerely thank you for your review and suggestions, which have helped us improve the quality of the paper.

Water tank trial:

In the original manuscript, we selected a set of data under good working conditions (Fig. 4b-d), and the relevant details of this condition were described in lines 481 to 484. You can also see in Figure 4e and f that we have studied the generator output power under different spectral peak periods. We set a total of 30 groups of irregular wave conditions, with 150 waves per group, and an average wave-making duration of 7 minutes. The tests were conducted under conditions with a spectral peak period of 1.1 s to 2.6 s and a significant wave height of 0.08 m to 0.18 m.

Open-sea trial:

In the revised manuscript, we have provided a detailed description of the experimental setup in line 358. As shown in Figure S13 and Figure 5d, the local average wind speed was approximately 0.93 m/s, the average wave period was approximately 1.93 s, and the wave height was approximately 0.1 m.

3. Please discuss the scalability of the system for larger deployments and any potential limitations (e.g., durability of materials, long-term performance in corrosive environments).

Author response: Thank you for your positive feedback on the manuscript and for your valuable suggestions. The self-powered monitoring buoy system centered on the chaotic pendulum wave energy converter (CP-WEC) demonstrates superior operational stability, compactness, high power density, cost-effectiveness, and deployability. Its scalability is mainly reflected in three aspects.

Firstly, the high-power density enables integration of multi-functional sensors (temperature, salinity, pressure, etc.) for comprehensive oceanographic data acquisition. Secondly, the modular design facilitates both autonomous operation and coordinated network configurations through distributed buoy arrays. Thirdly, according to the characteristics of regional waves, by adjusting the float counterweight, the resonant frequency can be adjusted to efficiently collect wave excitation energy of different frequencies, making the device have good environmental adaptability. Finally, by expanding the Internet of Things and satellite communications, real-time data transmission can be achieved, achieving unmanned and automated operation.

The proposed system presents several critical challenges requiring attention.

Environmental Resilience:

While designed for operational stability, supplemental protective measures remain essential to withstand extreme marine conditions (storm surges, abnormal wave patterns, tidal forces) that could compromise structural integrity.

Biofouling Management:

The accumulation of marine organisms (barnacles, algae, etc.) necessitates anti-fouling surface treatments and regular maintenance protocols to mitigate weight-induced buoyancy deviations in compact systems.

Material Degradation:

Though laboratory tests demonstrate the TENG’s mechanical durability, prolonged exposure to saline humidity and biological corrosion may accelerate dielectric layer deterioration, demanding enhanced material encapsulation.

Communication Reliability:

Offshore deployment introduces signal integrity risks from ambient noise interference.

Addressing these challenges will require iterative design refinement combined with adaptive maintenance strategies to ensure long-term system viability.

4. While the manuscript is generally well-written, a few sentences could benefit from minor grammatical adjustments for improved readability (e.g., "maintaining buoy equilibrium in marine environments" could be rephrased for clarity).

Author response: Thank you for your positive feedback on the manuscript and for your valuable suggestions. We have carefully reviewed the relevant sentences in the abstract and reworded it to improve clarity and readability. We appreciate your thorough review and constructive comments, which have greatly contributed to enhancing the quality of the manuscript.

Revised Text:

As a fundamental component of intelligent ocean development, the energy supply for unmanned oceanic equipment faces constraints imposed by traditional power generation methods. In-situ wave energy harvesting has recently garnered increasing attention. This study presents a chaotic pendulum-based energy harvesting mechanism designed to efficiently capture high-entropy and broadband wave energy. This approach departs from the conventional reliance on resonance to enhance wave energy converter (WEC) performance, instead enabling the conversion of disordered wave energy into regular mechanical energy. The tower-integrated generator design, combined with a charge-excitation circuit, enhances wave energy capture, achieving peak power densities of 56.7 $W/m^3 \cdot Hz$ for the triboelectric nanogenerator (TENG) and 192.3 $W/m^3 \cdot Hz$ for the electromagnetic generator (EMG). A wireless monitoring system is developed and validated through water tank experiments and open-sea trials. This work offers strong support for extending the operational endurance of unmanned intelligent marine equipment and facilitating the advancement of smart ocean development.

5. Please ensure tense consistency throughout the text, making sure that all verbs are in the same tense, especially when describing experiments and results, where the past tense is usually used.

Author response: Thank you for your valuable feedback. We have carefully reviewed the use of tenses throughout the manuscript and ensured consistency, particularly in the sections describing experiments and results, where the past tense has now been applied as appropriate. We appreciate your thorough review and constructive suggestions, which have helped us refine the manuscript further.

6. TENG and EMG should be used in full when they first appear in the abstract.

Author response: Thank you for your suggestion. As per your recommendation, we have written out TENG and EMG in full when they first appear in the abstract. We appreciate your careful review, which has helped improve the manuscript's adherence to conventions.

Revised Text (lines 20-22)**:**

The tower-integrated generator design, combined with a charge-excitation circuit, enhances wave energy capture, achieving peak power densities of 56.7 $W/m^3 \cdot Hz$ for the triboelectric nanogenerator (TENG) and 192.3 $W/m^3 \cdot Hz$ for the electromagnetic generator (EMG).

7. The PCB in Fig. 1b should belong to the TENG module.

Author response: Thank you for your comment. We have revised Figure 1b according to your suggestion, ensuring that the PCB is now correctly associated with the TENG module. We have also updated the figure legend to reflect this change. We appreciate your thorough review, which has helped clarify the figure.

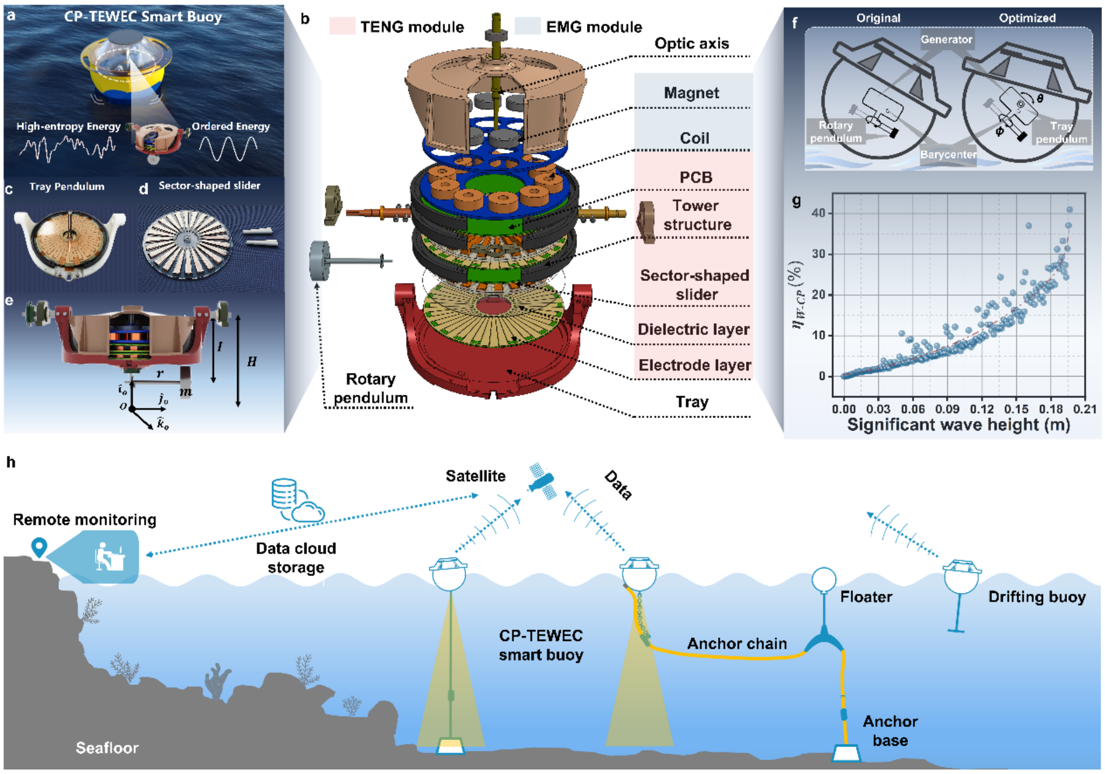


Fig. 1 Application scenario and scheme design of the CP-TEWEC.

8. The symbols in the formulas throughout the text should be consistent, for example, the top and bottom of Eq. 1-1 “d·σ” and “εrε0”, and the symbols “×” and “·”, etc. should be formatted consistently.

Author response: Thank you for your detailed comment. We have carefully reviewed the formulas throughout the manuscript and have standardized the formatting of symbols, ensuring consistency for expressions like "d·σ" and "εrε0" in Equation 1-1, as well as symbols like "×" and "·". We appreciate your thorough review and valuable suggestions, which have helped improve the consistency and clarity of the manuscript.

9. In the numerical simulations, the selection process for the material parameters and the source of the tool library are not explained. The author should include these details along with proper reference citations. Besides, please pay attention to the citation of equations in the article.

Details of COMSOL Simulations:

To improve reproducibility, we have expanded the description of the COMSOL simulation setup (revised in Supplementary Note 4 and 5):

The Simulations of EMG

The physical model of the EMG is geometrically modeled using the CAD module in COMSOL Multiphysics. Due to the symmetry of the EMG's geometric structure along the rotor axis, only one generation unit—1/10 of the original model—needs to be analyzed in the simulation. By applying sector symmetry and periodic boundary conditions, a three-dimensional simulation of the EMG can be obtained. The transient analysis and coil geometry analysis of the EMG are conducted using COMSOL's Rotating Machinery Module. The EMG generation unit model primarily consists of permanent magnets (black), copper coils (orange rings), and acrylic components (blue), with the remaining region defined as an air domain. Proper boundary condition settings are crucial for ensuring the accuracy of the simulation results. To simulate the EMG using the Rotating Machinery Module, a dynamic mesh rotation domain is configured. Consistent boundary pairs, including source and target boundaries, are assigned to the rotor and stator, respectively. Additionally, to capture the dispersion field, an air domain is defined at the rotating boundary, along with a middle air layer that separates the rotor and stator. Identical air domains are also added to the top and bottom layers of the model to ensure full enclosure.

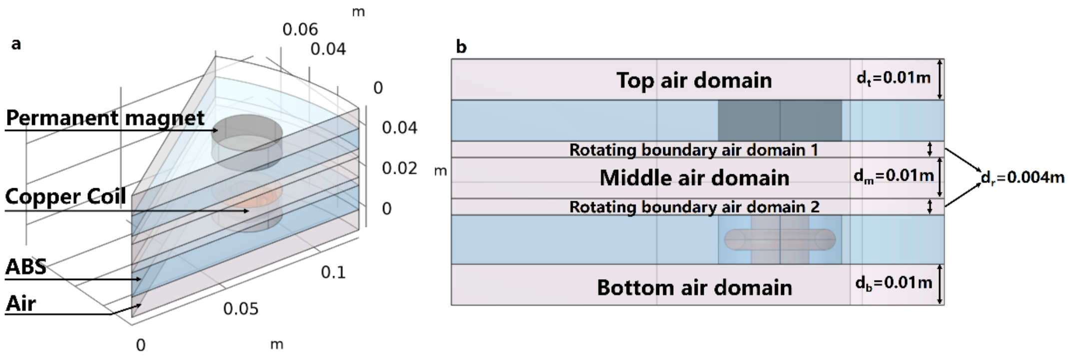


Figure N3 EMG physical model settings.

During the solution process, both the Magnetic Scalar Potential (MSP) and Magnetic Vector Potential (MVP) methods were employed. To obtain a three-dimensional simulation of the EMG, periodic boundary conditions were applied to the sectoral cross-sections of the generation unit. These boundaries were set as anti-periodic, indicating that the magnetic field directions of adjacent sectors are opposite. To ensure solver convergence, a zero magnetic scalar potential was imposed in the MSP region. The steady-state solution was used as the initial condition for the transient analysis. Finally, to enhance simulation accuracy, free triangular meshing was applied to refine the boundaries, while free tetrahedral meshing was used for the three-dimensional space.

The Simulations of TENG

The TENG module's power generation performance was analyzed using the COMSOL Multiphysics. To simplify the model and reduce computational complexity without losing generality, the three-dimensional TENG structure was equivalently transformed into a two-dimensional planar model based on its working principle. Specifically, the cross-section between the two metal induction electrodes was represented by three planar positions—left (i), center (ii), and right (iii)—for electrostatic simulation, as shown in the Fig. 2g.

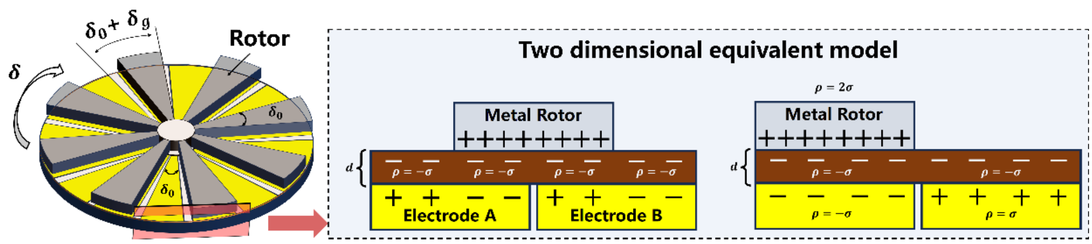


Figure N4 TENG physical model settings.

The materials and their corresponding relative permittivity and conductivity settings are shown in Table N1. Relative permittivity, also known as relative dielectric constant, is a parameter that measures the dielectric properties of a material and reflects its ability to store charge. Conductivity, which is the reciprocal of resistivity, characterizes the material's ability to transport charge.

Table N1 Relevant parameters of materials for various components in TENG module.

Name	Materials	Relative permittivity	Conductivity (S/m)
Air domain	Air	1	$3e^{-15}$
Metal electrode	Copper	∞	$5.81e^{7}$
Dielectrode film	PVC	10^{-13}	$1e^{-15}$

Since the established triboelectric generation model is a planar geometric structure in a two-dimensional space, a free triangular mesh, which offers greater applicability, was selected. Additionally, the triboelectric dielectric layer and the metal induction electrode were refined to ensure the accuracy and precision of the simulation analysis. In the electrostatic simulation environment, the surface charges of the magnet and metal coil were set to zero, while the four boundary walls of the air domain were grounded, with the initial electric potential set to 0 V. The Fermi energy levels of the two materials differ. Upon triboelectric power generation, Cu loses electrons, exhibiting positive polarity, while PVC gains electrons, exhibiting negative polarity. Therefore, by assigning a surface charge density to the materials, the potential distribution of the TENG module over a short cycle can be obtained.

Reviewer #2 (Remarks to the Author):

Overview and general recommendation:

The paper proposes a chaotic pendulum triboelectric-electromagnetic hybrid nanogenerator-based wave energy converter (CP-TEWEC) for marine equipment powering applications. The mechanism seeks to hybridize a rotary double-pendulum TENG with a standard EMG, in order to promote operational synergies and enhance energy harvesting from low frequency, low amplitude ocean wave action. An experimental study was conducted to demonstrate the proposed device, namely for supplying a self-powered marine temperature and humidity sensing system.

The Abstract is concise, yet informative and clear. The English grammar and structure require punctual improvements. The Introduction could benefit from some expansion and contextualization with regards to existing literature, as well as with regards to the work's motivation, objectives and contributions to reducing knowledge-gaps. This only becomes clearer near the end of the paper. The supplementary material was very useful and highly appreciated.

The paper is quite interesting and the findings pertinent, particularly the tank testing and sea trials. The CP-TEWEC concept is disruptive, but there are some matters that require clarification. For now, considering this and my comments, I recommend that the paper be subjected to major revisions. Even so, I encourage the authors to address the comments, which I hope will be helpful to them and, if adequately revised, should result in my approval for publication.

2.1. Major comments:

1- Line 34: reference 6 regards a case study of seawater electrolysis, and it is unclear how it corroborates the statements you make beforehand on autonomous IT systems (control units, sensors, etc.) at sea. I would recommend changing it (perhaps you could use one of the preceding references instead, in order to also mitigate reference lumping from Line 31);

Author response: Thank you very much for raising this concern.

Thank you for your careful review and suggestion regarding the citation in Line 37. We acknowledge that reference [6], which focuses on seawater electrolysis, does not directly support the discussion on autonomous IT systems, control units, and sensors in marine environments. To improve the relevance of our citations and reduce reference lumping in Line 31, we have replaced reference [6] with the following more appropriate sources:

Trends Biotechnol 23, 250-256 (2005) discusses the development of autonomous environmental monitoring systems, which aligns with our focus on distributed marine sensing networks.

Sens 10, 6948-6968 (2010) provides insights into sensor technologies for remote monitoring, supporting our discussion on real-time data acquisition in marine environments.

Nano Energy 88, 106199 (2021) highlights recent advances in energy harvesting technologies for powering distributed sensors, further reinforcing the context of our study.

We believe that these references better support our discussion on the challenges and advancements in autonomous marine monitoring technologies. Thank you for pointing this out, and we appreciate your constructive feedback.

2- Line 38: the resource can vary in time and space (for instance, there are even “hot-spots” of wave energy around the world), though it is always present at greater or lower magnitude. Though it is relatively predictable, abundant and broadly distributed, I would recommend you also highlight its greater density when comparing wave energy with wind and solar, for example, instead of mentioning the “site-independent exploitation”;

Author response: Thank you for your valuable suggestion. We agree that highlighting the greater energy density of wave energy compared to wind and solar energy provides a more comprehensive perspective on its advantages. In response, we have revised the statement (in red color) on line 38 as follows:

Revised Text (lines 37-45)**:**

Significantly, the in-situ harvesting of marine energy has been widely recognized by scholars as a promising solution to the endurance challenges confronting ocean monitoring systems[7–10]. Among marine renewable energy sources, wave energy exhibits distinct advantages, including abundant reserves, broad geographic distribution, and independence from diurnal cycle. Importantly, its power density significantly exceeds that of wind and solar energy[11,12]. These inherent characteristics highlight its potential for continuous energy extraction, motivating extensive global research efforts. Researchers have proposed developing novel WECs to power distributed ocean monitoring buoys[13–15], further advancing the vision of marine energy utilization for diverse applications.

3- Line 43: in the reference you cite they specify the “low efficiency of the EMG under irregular and low-frequency (< 5 Hz) ocean waves, the equipment manufacturing and maintenance costs are extremely high”. There is also a discussion on the devices’ environmental sustainability, corrosion resilience and other topics. Perhaps you could highlight some of these to better contextualize the limitations of EMGs. I would also recommend discussing, briefly, non-EMG alternatives (aside from TENGs, naturally) and their limitations, in parallel to what you do for EMGs. Alternatively, you could better explain why you give emphasis to EMGs within the scope of WEC technology. I understand they will be considered further along the paper, but EMGs should be better introduced at this point, in order for the reader to understand why they are mentioned in detriment of non-EMG options. I also felt that the contextualization was a bit generic. It would be more interesting to see some more discussion on existing literature (e.g., “Author X studied TENGs in a buoy for Y purpose, from which they obtained Z results”, “Authors A and B used a novel TENG configuration to power a C device, at sea”, etc.) in the Introduction, as well as a schematic or better summary of the triboelectrification and electrostatic induction processes in TENGs;

Author response: Thank you for your insightful feedback. Following your suggestion, we have rewritten the introduction section of the paper to more clearly articulate our perspectives. First, in the revised version, we have added an introduction to the rotational pendulum-based energy harvesting mechanism at lines 46 to 64. This mechanism is expected to mitigate the dependence of traditional WECs on resonance effects and is more suitable for capturing high-entropy, broadband wave energy. Additionally, we have highlighted its current limitations. Next, in lines 65–108, based on the dynamic characteristics of the aforementioned mechanism, we introduce three types of power generation technologies. Through a comparative analysis of their features and a literature review, we evaluate the major advantages and disadvantages of these technologies. Furthermore, in lines 109–123, we highlight the benefits of combining TENGs and EMGs, particularly in expanding the operational bandwidth of the generator, which leads to the introduction of our research in the subsequent sections.

4- Lines 46-48: you should address some additional disadvantages/limitations of existing TENG technologies (e.g., as done briefly in Line 57), which can also help you elaborate on the motivation for your work and its contribution towards the current state-of-the-art. You should also be mindful of the sentence that starts in Line 48, as it gives the impression that the TENGs reported in the three references you provide were all tested at sea (which is not the case, if I understood correctly – they were mainly subjected to laboratory demonstration);

Author response: Thank you for your constructive comments. To address your concerns, we have updated the text on lines 89-112 to provide a more detailed discussion of existing limitations of TENG technologies. The revised section reads:

Revised Text:

TENGs are distinguished by their high efficiency at low frequencies, simple structures, and lightweight design[28–30]. In wave energy applications, TENGs are mainly classified based on their operating modes, including contact-separation mode[31,32], rolling-freestanding layer mode[33], and sliding mode[34,35]. The contact-separation mode, characterized by its simple structure, typically utilizes arch-shaped or spring-supported configurations. These researcher-developed structures excel in harvesting high-frequency and large-amplitude wave energy. Among the various TENGs, the rolling freestanding-layer TENG circumvents electrostatic shielding effects, with tower-like and arc-shaped configurations being evolutions of this concept[36]. These designs greatly improve the long-term stability of TENGs by minimizing direct friction between the contact surfaces. However, a critical limitation arises from the restricted effective contact area between dielectric layers, leading to suboptimal charge transfer and diminished power output. Additionally, the inertial ball inside the device weakens the wave-induced motion response, functioning in a manner akin to a tuned mass damper (TMD)[37], which often requires stronger external excitations in real marine environments (such as waves exceeding 0.5 m in height or wind speeds surpassing 9 m/s)[38]. In contrast, the rotary pendulum-type TENG leverages sliding mode to significantly increase the effective contact area of dielectric layers [39–41], enabling faster charge transfer rates and prolonged retention within a two-dimensional plane while maintaining low mechanical complexity. Based on potential energy storage/release strategy, Cao et al.[42] introduced a TENG featuring a swing-rotation switching mechanism to efficiently capture low-frequency mechanical energy (0.3~5 Hz). This design achieves a bandwidth 4 times broader than that of traditional cylindrical pendulum TENGs, with peak power densities of 10.1 W/m³ at 1.8 Hz and 15.4 W/m³ at 5 Hz. However, the need to maintain stable floater oscillations typically requires miniaturization of the power generation system, fundamentally limiting potential output power enhancement.

5- Line 50: this is a pertinent development, but it should be better explained how the EMGs and TENGs complement one another and how they can be integrated into an effective hybrid system. On the latter, you could develop a bit more on some works found in literature. For example, there are relatively recent studies in which TENGs are even incorporated into EMG-based WECs, such as Salter's Duck, E-Motions, etc. Note also that, when you state that the hybridization promotes "broadening the operational bandwidth of WECs", you should be mindful that i) the power output of EMGs and TENGs can be quite distinct, in terms of magnitude, ii) WECs operate optimally under resonance, and while TENGs can provide novel motion response "peaks" that can be explored, promoting resonance is usually achieved through natural frequency tuning, latching and other types of control mechanisms (so the wave period/frequency would matter as well, extending from what you discuss in Line 62), and iii) as stated in line 60, in some instances, TENGs can "mitigate the wave-induced motion response, functioning in a manner akin to a tuned mass damper". On point iii), the reference you provide even states that "Tuned mass dampers (TMDs) are effective in a small range around the resonance frequency, and they are sensitive to the working conditions";

Author response: Thank you for your constructive comments. We recognize that there are some issues in our language expression. It is well understood that traditional WECs rely on resonance to achieve higher energy conversion efficiency. As generators, TENG and EMG are likely to reach peak conversion efficiency at their resonance frequency, thereby constraining the operational bandwidth of WECs.

Therefore, we proposed a chaotic pendulum-based energy harvester. The novel design shifts the traditional thinking of enhancing wave energy converter performance through resonance dependence. Instead, it utilizes wave steepness excitation to trigger high-amplitude responses under low-energy conditions, thereby broadening the effective operational bandwidth of WECs. This approach not only reduces the complexity of the control system but also facilitates the capture of high-entropy wave energy.

However, an inherent challenge lies in the efficient collection of broadband mechanical energy generated by this mechanism. To address this, we leverage the complementary technical characteristics of TENG and EMG, integrating their advantages to effectively harvest the mechanical energy of the energy capture system. This leads to the concept of extending the operational bandwidth of the generator. Following your suggestion, we have also analyzed the current research status and advantages of hybrid generators in lines 109–123.

6- Line 68: while I understand some of the advantages of the hybridization, won´t the matter of mass distribution and its influence on the floater response remain unresolved (or possibly worsened)? Also, since you are proposing a double-pendulum with a chaotic behavior, and given the stochastic nature of waves, won´t this affect the predictability and stability of the power output? The perspective of decoupling the system from the floater's dynamic response is interesting, but the power regularization process doesn´t seem sufficiently evident to me, at this stage. Perhaps a supporting Figure or description could make it clearer (or referring earlier to Figure 1);

Author response: Thank you for your thoughtful comments. Your concerns regarding the impact of mass distribution on floater stability, the chaotic behavior of the double-pendulum system, and the need for greater clarity on the power regularization process are highly appreciated. We have made the following revisions and additions to address these issues:

Mass Distribution and Floater Stability:

We acknowledge that the mass distribution of the hybrid system could influence floater stability. However, the proposed design incorporates careful optimization of the double-pendulum system to minimize this effect. Specifically, the pendulum's mass and placement are balanced relative to the floater's center of buoyancy to ensure stable operation. Additionally, as observed from the free decay motion curve of the buoy in the appendix, the decoupling mechanism ensures that the generator operates independently of the floater's dynamic response, thereby mitigating the adverse effects caused by uneven mass distribution.

Chaotic Behavior and Power Output Predictability:

We agree with the reviewers' perspective regarding the potential impact of wave randomness and chaotic behavior on the predictability and stability of power output. Indeed, the randomness and chaotic characteristics of waves can potentially lead to instability in the system's power output. Therefore, in our design, we have leveraged the feature of the TENG, wherein the open-circuit voltage is independent of the input frequency. Additionally, for the EMG, we employed the LTC3588 circuit for rectification and voltage regulation, ensuring effective power balancing under varying wave conditions.

Enhanced Description and Supporting Figures:

To provide greater clarity on the power regularization process and the decoupling mechanism, we have added a description in Supplementary Note 1:

Revised Text:

Supplementary Note 1. Description of decoupling mechanism

The left panel of the figure depicts a class of rotational pendulum-based WECs. When the generator's mass is comparable to that of the floating body, its barycenter undergoes continuous displacement under the influence of incident waves. This displacement significantly affects the floater, making it highly sensitive to shifts in the generator's barycenter. Consequently, instability arises, suppressing the floater's regular oscillations and inducing a strong negative coupling effect. Even minor asymmetries in the barycenter of small floating bodies can substantially alter their hydrodynamic response.

To mitigate this issue, an effective strategy is to decouple the generator's barycenter from that of the floating body, ensuring that the generator maintains a stable barycenter relative to the floater under wave excitation. As illustrated in the right panel, this decoupling is achieved by enclosing the generator within the floating body and introducing a tray pendulum. When waves act upon the floater, it tilts, triggering the adaptive reciprocating motion of the tray pendulum. Simultaneously, the counterweight drives the rotary pendulum, stabilizing the wave energy conversion process and maximizing energy extraction from the incident waves.

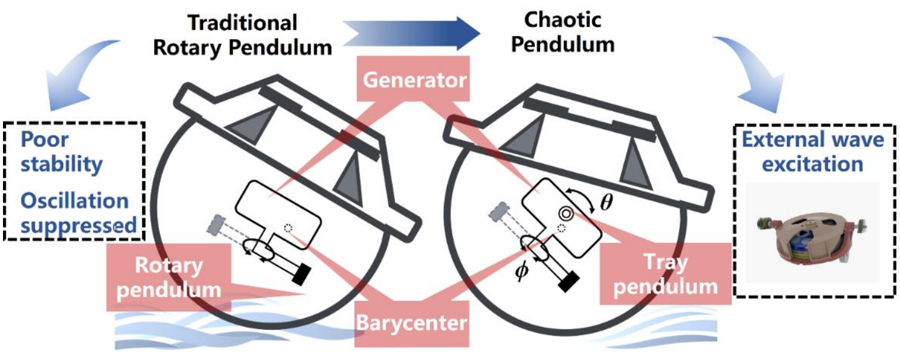


Figure N1 The origin and characteristics of chaotic pendulum energy capture mechanism.

7- Line 79: how do these values pair up against other case studies found in literature? It would be interesting to have said comparison, in order to see how well your device fairs against others. I think this was your goal with Figure 4h, but it would be helpful to have, at least, a brief mention here of that comparison. Furthermore, when you state that there is a "4.6-fold increase in the generator's energy storage capacity", what is the reference to which you are comparing it with? You could also discuss the difference in the individual EMG and TENG's performance from the hybrid system;

Author response: Thank you for your insightful feedback. To address your concerns, we have made the following revisions to enhance the discussion on performance comparison and to clarify the reference for the 4.6-fold increase:

Performance Comparison with Literature:

We agree that providing a comparison with other case studies in the literature is essential for contextualizing the performance of our device. While Figure 4h presents a detailed comparison of power densities, we have added a brief mention in the text to highlight these findings:

Revised Text: line 129

The hybrid TENG-EMG system achieves remarkable peak power densities of 56.7 $W/m^3 \cdot Hz$ (TENG) and 192.3 $W/m^3 \cdot Hz$ (EMG), representing 28.3 folds and 11.3 folds improvements over Han's work, respectively.

Clarification of the Reference for the 4.6-Fold Increase:

We acknowledge that the reference for the "4.6-fold increase" should be clarified. The text has been revised to specify the baseline:

Revised Text: line 130

We further propose a novel charge excitation circuit, which enhances the generator's energy storage capacity by 4.6 folds compared to conventional DB107 rectifier-based circuit.

8- Figure 1g: the significant wave height values are in model (reduced-) scale or prototype (full-) scale? Also, why did you consider these specific Hs and Tp values? Are these the representative conditions of your case study region?;

Author response: Thank you for your thoughtful questions regarding Figure 1g. We have revised the manuscript to clarify the model scale, the choice of H_s and T_p values, and their relevance to the case study region:

Model Scale Considerations:

The significant wave height (H_s) mentioned in Figure 1g corresponds to calculations performed at the prototype scale of the model. This clarification will be explicitly stated in the revised manuscript to prevent any potential confusion.

Revised Text in "Fabrication of the buoys"

In the experiments, a full-scale (1:1) prototype was used to ensure the experimental conditions closely resemble real-world marine environments. All structural parameters, including dimensions, mass distribution, and hydrodynamic properties, were maintained identical to those of the actual deployed system. This approach eliminates scale effects that may arise in reduced-scale models, ensuring that the experimental results accurately reflect the device's real-world performance. The measured parameters in this study, such as wave-induced motion, power generation efficiency, and structural stability, therefore correspond directly to the full-scale system.

Rationale for Selecting Specific H_s and T_p Values:

The selection of H_s and T_p was based on the typical oceanic conditions of the study area. These wave conditions were determined through an analysis of historical wave data from the region.

9- Check if all the parameters of Equations 1- were defined in the text. Can you also please clarify the differences between your Equation 1-4 and the one presented in reference 60, Equation 3b, as well as the definition of the force term (adhesion versus attraction)? Prior to Figure 2, you should have mentioned that the simulations were undertaken with COMSOL and detail a bit more how they were setup, in order to promote reproducibility. It would be equally pertinent, for validation and uncertainty analysis purposes, to have a better perception of the correlation between the expected values from the mathematical formulas versus those of the COMSOL simulations, since you only provide a single voltage value reference (430 versus 466.67 V);

Author response: Thank you for your detailed feedback regarding the parameter definitions, simulation methodology, and the correlation between mathematical and simulation results. We have made the following revisions to address your concerns.

1. Parameter Definitions in Equations 1-:

We have thoroughly reviewed the manuscript to ensure that all parameters in Equations 1- are defined in the text.

2. Differences Between Equation 1-4 and Reference 60:

Our Equation 1-4 specifically describes the electrostatic adhesion force generated by the interaction between the slider and the dielectric layer in the rotary triboelectric nanogenerator. In contrast, Equation 3b in reference 60 focuses on the attractive force between charged surfaces under general conditions. The key difference lies in the incorporation of geometric parameters (r_1 and r_2) in our equation, which is tailored to the rotary design of the TENG module in this study. This customization ensures that Equation 1-4 accurately reflects the force dynamics within our device.

3. Details of COMSOL Simulations:

To improve reproducibility, we have expanded the description of the COMSOL simulation setup:

The Simulations of EMG

The physical model of the EMG is geometrically modeled using the CAD module in COMSOL Multiphysics. Due to the symmetry of the EMG's geometric structure along the rotor axis, only one generation unit—1/10 of the original model—needs to be analyzed in the simulation. By applying sector symmetry and periodic boundary conditions, a three-dimensional simulation of the EMG can be obtained. The transient analysis and coil geometry analysis of the EMG are conducted using COMSOL's Rotating Machinery Module. The EMG generation unit model primarily consists of permanent magnets (black), copper coils (orange rings), and acrylic components (blue), with the remaining region defined as an air domain. Proper boundary condition settings are crucial for ensuring the accuracy of the simulation results. To simulate the EMG using the Rotating Machinery Module, a dynamic mesh rotation domain is configured. Consistent boundary pairs, including source and target boundaries, are assigned to the rotor and stator, respectively. Additionally, to capture the dispersion field, an air domain is defined at the rotating boundary, along with a middle air layer that separates the rotor and stator. Identical air domains are also added to the top and bottom layers of the model to ensure full enclosure.

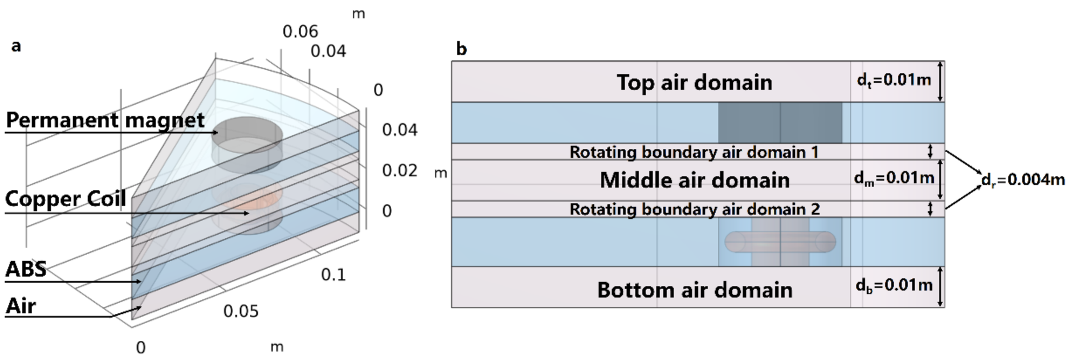


Figure N3 EMG physical model mettings.

During the solution process, both the Magnetic Scalar Potential (MSP) and Magnetic Vector Potential (MVP) methods were employed. To obtain a three-dimensional simulation of the EMG, periodic boundary conditions were applied to the sectoral cross-sections of the generation unit. These boundaries were set as anti-periodic, indicating that the magnetic field directions of adjacent sectors are opposite. To ensure solver convergence, a zero magnetic scalar potential was imposed in the MSP region. The steady-state solution was used as the initial condition for the transient analysis. Finally, to enhance simulation accuracy, free triangular meshing was applied to refine the boundaries, while free tetrahedral meshing was used for the three-dimensional space.

The Simulations of TENG

The TENG module's power generation performance was analyzed using the COMSOL Multiphysics. To simplify the model and reduce computational complexity without losing generality, the three-dimensional TENG structure was equivalently transformed into a two-dimensional planar model based on its working principle. Specifically, the cross-section between the two metal induction electrodes was represented by three planar positions—left (i), center (ii), and right (iii)—for electrostatic simulation, as shown in the Fig. 2g.

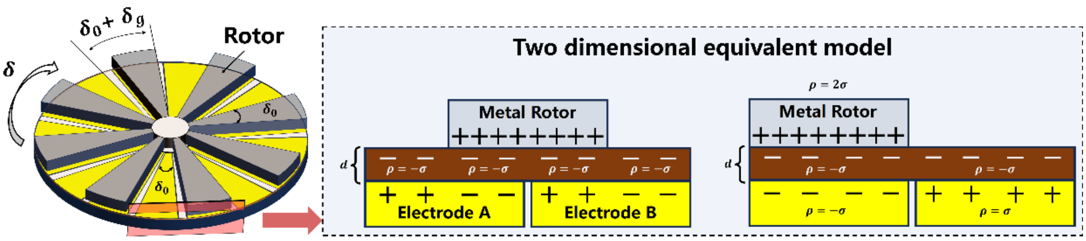


Figure N4 TENG physical model settings.

The materials and their corresponding relative permittivity and conductivity settings are shown in Table N1. Relative permittivity, also known as relative dielectric constant, is a parameter that measures the dielectric properties of a material and reflects its ability to store charge. Conductivity, which is the reciprocal of resistivity, characterizes the material's ability to transport charge.

Table N2 Relevant parameters of materials for various components in TENG module.

Name	Materials	Relative permittivity	Conductivity (S/m)
Air domain	Air	1	$3e^{-15}$
Metal electrode	Copper	∞	$5.81e^{7}$
Dielectrode film	PVC	10^{-13}	$1e^{-15}$

Since the established triboelectric generation model is a planar geometric structure in a two-dimensional space, a free triangular mesh, which offers greater applicability, was selected. Additionally, the triboelectric dielectric layer and the metal induction electrode were refined to ensure the accuracy and precision of the simulation analysis. In the electrostatic simulation environment, the surface charges of the magnet and metal coil were set to zero, while the four boundary walls of the air domain were grounded, with the initial electric potential set to 0 V. The Fermi energy levels of the two materials differ. Upon triboelectric power generation, Cu loses electrons, exhibiting positive polarity, while PVC gains electrons, exhibiting negative polarity. Therefore, by assigning a surface charge density to the materials, the potential distribution of the TENG module over a short cycle can be obtained.

4. Correlation Between Theoretical and Simulation Results:

The mathematical model predicts an open-circuit voltage of 466.67 V (Equation 1-1), while the COMSOL simulation yields a result of 430 V, with a relative deviation of 7.8%. This deviation can be attributed to assumptions in the theoretical model, such as uniform charge distribution and idealized material properties. Despite these simplifications, the small discrepancy between the two results confirms the reliability of both the theoretical and simulation approaches.

Revised in lines 245-250.

10- Line 220: could you please elaborate a bit more on these promising outcomes with the inclusion of the CEC? Also, note that your sentence in Line 226 hints at a beneficial operational overlap of the TENG and EMG, as they compensate each other in terms of operational range. There might also be a typo here, as I believe you wanted to write "19 mW" or "0.19 W". It is also strange to see the 10 mW value for the TENG, as the maximum average power seems to be closer to 20 mW (at least, visually): Could you also put Figure 3f and h with the same range for the average and peak power values, please? Lastly, could you also clarify what was the amplitude of the rotations?;

Author response: Thank you for your valuable comments. To address your suggestions, we have elaborated on the outcomes of including the charge excitation circuit (CEC) and clarified the operational overlap between the TENG and EMG modules. Below are the specific revisions:

1. Outcomes of Including the CEC (Line 220)

We have expanded the discussion to emphasize the performance improvements enabled by the CEC:

The introduction of the CEC significantly enhances the energy storage capability of the TENG. In fact, we observed that the charging excitation circuit increased both the charge transfer efficiency and the energy storage rate.

Revised Text (lines 302 to 304):

To maximize energy extraction, we designed a charge extraction circuit (CEC, Fig. 3d) that synchronizes with the TENG's cycles. At 60 rpm and load resistance R_l = 7 MΩ, the CEC-augmented TENG achieves a 233.8 μA current pulse (Fig. 3e), delivering 0.1 J in 5 s. Fig. 3f reveals the CEC's power optimization. At R_l = 7 MΩ, the TENG hits peak efficiency (20 mW avg., 0.2 W peak), outperforming rectifier bridges (DB107) by 22.5 folds in charge density (Fig. S4). Capacitor charging tests (Fig. 3g) confirm the CEC's 4.6 folds rate enhancement, attributable to reduced charge recombination during energy transfer phases.

2. Clarification of the overlapping operating range and power values of the TENG and EMG

Regarding the overlapping operating range between the TENG and EMG, we mean that the TENG efficiently captures energy under low-frequency conditions, while the EMG performs well under high-frequency conditions. Therefore, the complementarity between the two allows the hybrid system to cover a broader frequency range, thereby enhancing overall performance. In the revised text, we will further clarify this point and modify the sentences to ensure greater clarity in expression.

Revised Text (lines 273 to 281)**:**

At 60 rpm and load resistance R_l = 7 MΩ, the CEC-augmented TENG achieves a 233.8 μA current pulse (Fig. 3e), delivering 0.1 J in 5 s. Fig. 3f reveals the CEC's power optimization. At R_l = 7 MΩ, the TENG hits peak efficiency (20 mW avg., 0.2 W peak), outperforming rectifier bridges (DB107) by 22.5 folds in charge density (Fig. S4). Capacitor charging tests (Fig. 3g) confirm the CEC's 4.6 folds rate enhancement, attributable to reduced charge recombination during energy transfer phases. The EMG's matched-load power (0.19 W at R_l = 51 Ω, 60 rpm, Fig. 3h) underscores its high-frequency advantage, complementing the TENG's low-frequency dominance. This frequency-selective synergy expands the hybrid nanogenerator's operational bandwidth, boosting comprehensive power by 51.2 % relative to standalone modules.

3. Regarding the power values

The reviewer pointed out an error in the power values on line 226. After a thorough reexamination, we identified the mistake and have corrected it in the revised manuscript.

Revised Text 1:

At R_l = 7 MΩ, the TENG hits peak efficiency (20 mW avg., 0.2 W peak), outperforming rectifier bridges (DB107) by 22.5 folds in charge density (Fig. S4).

Revised Text 2:

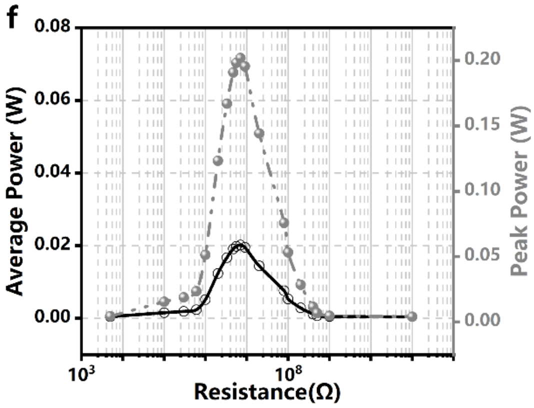
The EMG's matched-load power (0.19 W at R_l = 51 Ω, 60 rpm, Fig. 3h) underscores its high-frequency advantage, complementing the TENG's low-frequency dominance.

4. Adjusting the Range for Average and Peak Power Values in Figure 3f and 3h

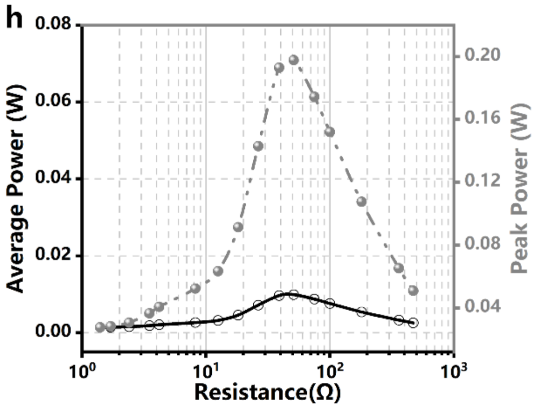
We have updated Figure 3f and 3h to ensure that both figures use the same range for average and peak power values, providing a consistent comparison across the two figures. Additionally, we have revised the figure captions to reflect this update:

Revised figure:

f



h



5. Clarifying the Amplitude of the Rotations

During the experiments, the TENG and EMG modules were subjected to rotational excitations with an amplitude of approximately 11.75 rad/s (or 112 rpm).

11- Line 272: likely you have resonance occurring at that period of about 1.9 s, as it matches the peak from the FFT analysis and the free decay test intervals. It is curious to see such a regular free decay pattern from the device, as I would expect a more complex pattern, given its double-pendulum and chaotic nature. Regarding the numerical versus experimental tests, could you please clarify a bit better the testing conditions? Most of the results you provide refer to a single wave height value, but here you compare multiple values. Did you conduct tests with only one irregular wave case or with different wave conditions?;

Author response: Thank you for your detailed observations and questions.

We conduct tests with different wave conditions. The testing conditions of numerical versus experimental tests are as follow:

Experimental tests

Revised Text (lines 480 to 483)**:**

A total of 30 irregular wave conditions were established, with each condition consisting of 150 wave cycles. The average duration of each wave generation was 7 minutes, with spectral peak periods ranging from 1.1 s to 2.6 s and significant wave heights between 0.08 m and 0.18 m.

Fig. 4b-d present a selected set of data that represents one of the better-performing conditions. As shown in Fig. 4e-f, we also conducted a study on the generator output power under different spectral peak periods.

12- Figure 5: did you conduct tests to verify humidity, temperature and other factors that can affect the EMG and TENG's operational efficiency at sea?; Did you consider extreme events and survivability testing?;

Author response: We appreciate the reviewer's concerns regarding the impact of humidity, temperature, and extreme sea conditions on the operational efficiency of the EMG and TENG.

In the current experiments, our focus has been on tests conducted under controlled laboratory conditions, with particular emphasis on the durability and stability of the equipment under typical marine conditions. We have observed that, in the pool experiments, humidity did not significantly affect the data signals or the operational efficiency of the equipment. However, the effects of variations in environmental factors such as temperature and humidity on the long-term operation of the equipment have not been fully evaluated, particularly under the complex conditions of actual marine environments.

Regarding extreme sea conditions and survivability testing, our current experiments primarily focus on simulating typical marine environmental conditions and do not include extreme weather or wave conditions. We recognize that these extreme conditions may significantly impact the long-term stability and survivability of the equipment. Therefore, future research will focus on further testing under extreme sea conditions (such as high waves and high wind speeds) and evaluating the effects of these factors on the performance of the EMG and TENG systems.

We will further refine the numerical computations and experimental design in this area to ensure that future research encompasses a broader range of environmental conditions and provides more comprehensive validation of the equipment's performance.

13- Line 314: note that, for operational purposes, you should consider that, at sea, you have variable wave height, period and direction, which can affect the performance of your device over time. It might also be more pertinent to design the device's resonant frequency to match the most energetic wave conditions at the deployment site, which are not necessarily the average ones. You should also consider how this can affect the floater's stability: a WEC usually seeks larger motions to extract energy, but this can be counterproductive for floating structures and systems who are sensitive to sudden and large motions. Also, it should be clearer to the reader when you are transitioning from the tank tests to the sea trials. I would advise including a connecting paragraph and/or splitting it into two sub-sections. Lastly, did you notice whether the wind was an important or negligible factor in the device's performance?

Author response: We would like to thank you for the thorough review of our work and the valuable suggestions. In fact, your recommendations align closely with our design mentality.

1. Wave conditions

Existing WECs primarily rely on resonance effects to achieve high power output. However, resonance effects typically exhibit a narrow frequency bandwidth, whereas the spectrum of ocean waves is broadly distributed. As a result, existing devices must actively or passively maintain resonant conditions over time, which increases the complexity of system design, operational control difficulties, and maintenance costs. Therefore, we propose a chaotic pendulum mechanism that utilizes wave steepness as the excitation condition. The pendulum's adaptive oscillations enhance the buoy's stability and power output. Additionally, our analysis of the dynamics of the buoy and chaotic pendulum reveals that when the wave steepness exceeds a critical threshold, the pendulum's motion transitions into chaotic behavior, making the power output unpredictable. Therefore, our current work in dynamics focuses on how to constrain the motion of the chaotic pendulum system within the critical range.

2. Transition from pool testing to offshore trials

We sincerely appreciate the reviewer's suggestion regarding the transition between the pool testing and the offshore trials. To better present the experimental background and the practical conditions of the offshore trials, we have divided this section into two subsections.

3. Impact of wind on device performance

In our wave tank experiments, the impact of wind was not considered independently, as we utilized a wave height gauge to calculate the wave steepness. The inclusion of wind could potentially affect our testing of the dynamic performance of the device's floating body and the built-in pendulum. Furthermore, we believe that the formation of waves is directly related to wind speed. In real-world marine environments, the effects of wind may interact with waves, significantly influencing the stability and performance of the device. Therefore, we plan to further assess the impact of wind in future research, particularly under conditions of higher wind speeds.

14- Line 419: you had already mentioned the dimensions of the wave tank. Did you evaluate potential wall effects and re-reflections off the tank boundaries affecting your measurements? Did you compare the generated waves with those actually intended to make (calibration procedures)? Also, do you reckon that wave directionality can impact your device's performance or not, based on the wave tank experiments? Was the sampling rate of 1 kHz the same for all the measurement systems? Lastly, were you able to measure the floater motions in real time with the electrometers?

Author response: We sincerely appreciate the reviewers' thorough examination of our experimental methodology and their valuable suggestions.

1. Boundary Effects and Wave Reflection in the Flume

We carefully considered the boundary effects of the wave flume, particularly the reflection of waves at the flume walls. To minimize this influence, we specifically selected an appropriate testing area (x = 50 m, y = 0.8 m) to reduce the interference of reflected waves on the measurement results. Additionally, prior to the experiments, we conducted wave calibration to ensure that the generated waves closely matched the target waves. Specifically, in the irregular wave experiments, the peak spectral period (T_p) and significant wave height (H_s) were the key parameters for defining different test conditions. However, due to system errors and the inherent randomness of irregular waves, it was necessary to further process the collected wave data. To achieve this, we employed real-time wave height measurements using wave gauges and applied spectral and time-domain analysis methods. By utilizing programmed calculations, we accurately determined the actual T_p and H_s, ensuring proper calibration of the experimental conditions.

2. Wave Directionality

In nonlinear systems driven by ocean waves, wave directionality can influence the initial state of the device, such as the initial angle and velocity of the pendulum. Even under nearly identical wave conditions, slight variations in wave direction and amplitude can lead to significantly different system trajectories, thereby affecting the device's performance and response. For the chaotic pendulum system, this effect is particularly pronounced at higher driving frequencies or larger wave amplitudes, where the system's nonlinear characteristics become more evident and its sensitivity to initial conditions increases. Although our experiments primarily focus on wave conditions in a single direction, we acknowledge that variations in wave directionality in real ocean environments may impact the energy capture efficiency of the device.

To address this, we plan to conduct wave directionality tests in future studies to evaluate its influence on device performance. In the current experiments, due to the constraints of the wave flume, we were unable to fully simulate the effects of wave directionality.

3. Sampling Rate of the Measurement System

Upon review, we identified an error and have made the necessary corrections. The sampling rates of the various measurement systems are as follows:

Digital Inclinometer (YGQ300-D Model): Used for static water free decay tests of the buoy and the motion response tests under wave excitation. The sampling frequency ranges from 1 Hz to 50 Hz.

Power Performance Testing System (Electrostatic Meter): The sampling frequency is 1 kHz.

Dynamic Signal Testing and Analysis Platform (DHDAS Model): The sampling frequency is 1 kHz. This system records the response angles of the buoy, the tray oscillation angle, and the rotational pendulum angle in real-time using a hollow angular displacement sensor.

Digital Wave Height Meter (YWH200-DXX Model): The sampling frequency is 1 kHz. It assists in recording the actual wave height and period under irregular wave conditions.

Revised Text (lines 468 to 470)**:**

The dynamic signal testing and analysis platform (DHDAS Model) also operates at a sampling frequency of 1 kHz, recording the response angles of the buoy, tray oscillation angle, and rotational pendulum angle in real-time using a hollow angular displacement sensor.

4. Real-time Measurement of Buoy Motion

We used the digital inclinometer (YGQ300-D model) to measure the buoy's motion in real-time. This sensor is capable of capturing the dynamic changes of the buoy under wave action, providing accurate motion data for the experiment. However, we believe that it is currently not feasible to use the electrostatic meter to measure the buoy’s motion in real-time.

2.2. Minor comments:

1- You might want to consider alternative or additional keywords to better showcase the scope and content of your paper;

Author response:

We sincerely appreciate the reviewers' suggestions regarding the selection of keywords. We fully understand that choosing appropriate keywords is crucial for accurately representing the theme and content of the paper. In the revised manuscript, we have incorporated the reviewers' recommendations by adding or adjusting certain keywords to better reflect the scope and focus of our research. Below are the updated keywords we have considered:

Keywords:

Wave Energy Converter (WEC)；

Electromagnetic Generator (EMG)；

Triboelectric Nanogenerator (TENG)；

Chaotic pendulum;

Unmanned monitoring buoy;

2- Avoid lumping of references, as done in Line 31, 36 or 40, among others. In the case of Line 40, the number of references is very high, and I believe the paper would benefit from a summarized description of existing case studies related to said references. 3 references should be provided at once, maximum, in order to corroborate your statement;

Author response: We sincerely appreciate the reviewers' valuable suggestions regarding reference citations. We fully understand the importance of avoiding excessive clustering of references, as this improves the clarity and readability of the manuscript while ensuring that each study is adequately presented. In the revised manuscript, we have made the necessary modifications to address this concern. Specifically, we have undertaken the following adjustments:

Avoiding clustered citations: We have ensured that no more than four references are cited at a time. This allows each study or case to be more clearly explained, helping readers better understand the contributions of individual works.

Providing concise literature summaries: We have refined our discussion of the relevant literature by summarizing key studies, highlighting their findings, and contextualizing them within the broader research landscape. This revision helps readers grasp the current progress and challenges in the field more effectively.

3- Some minor English grammar errors were detected. Please double-check the paper and correct them, accordingly;

Author response: We appreciate the reviewers' comments on language issues. We have carefully reviewed the manuscript for grammatical errors and made the necessary revisions. We are grateful for the reviewers' insights and assure a thorough language check in the revised manuscript. If the reviewers have any additional suggestions or specific areas that require further attention, please do not hesitate to let us know.

4- Line 44: instead of "wave energy harvesters", you can simply use the abbreviation WECs;

Author response: We appreciate the reviewers' suggestions regarding language usage. In accordance with your recommendation, we have replaced "wave energy harvesters" with the abbreviation "WECs" throughout the manuscript.

5- Line 56: eliminate or reduce considerably? Please confirm what you mean;

Author response: We appreciate the reviewers' attention to this section. In line 56 of the original manuscript, our intention was to emphasize "a reduction" or "a significant reduction." To ensure greater clarity and accuracy in our expression, we have carefully reviewed the sentence and made the following revisions:

Revised Text (line 93):

These designs greatly improve the long-term stability of TENGs by minimizing direct friction between the contact surfaces.

6- Line 63: aside from avoiding reference lumping, I think some of the references are not specific to rotary pendulum-type TENGs. Hence, you should consider removing them;

Author response: Thank you for your valuable suggestions. We have carefully reviewed the references cited in line 63 and found that some of them are less relevant to the corresponding statement. In response to the reviewers' recommendations, we have restructured the introduction section and refined the selection of references in the revised manuscript to ensure that they more accurately support the core content of the paper.

7- The resolution of Figure 1, in particular the letters, should be slightly enhanced for clearer reading;

Author response: We sincerely thank the reviewer for pointing out the issue regarding the resolution of Figure 1. We have revised Figure 1 to ensure higher resolution, especially for the labels and annotations. The updated figure now provides clearer visibility of all details, making it easier for readers to interpret the schematic and design of the chaotic pendulum triboelectric-electromagnetic hybrid nanogenerator (CP-TEWEC). The revised figure has been embedded in the manuscript with a resolution of 300 dpi, ensuring that all text and graphical elements are sharp and legible. We believe that these adjustments have addressed the reviewer's concern, and the updated figure now meets the high standards of Nature Communications.

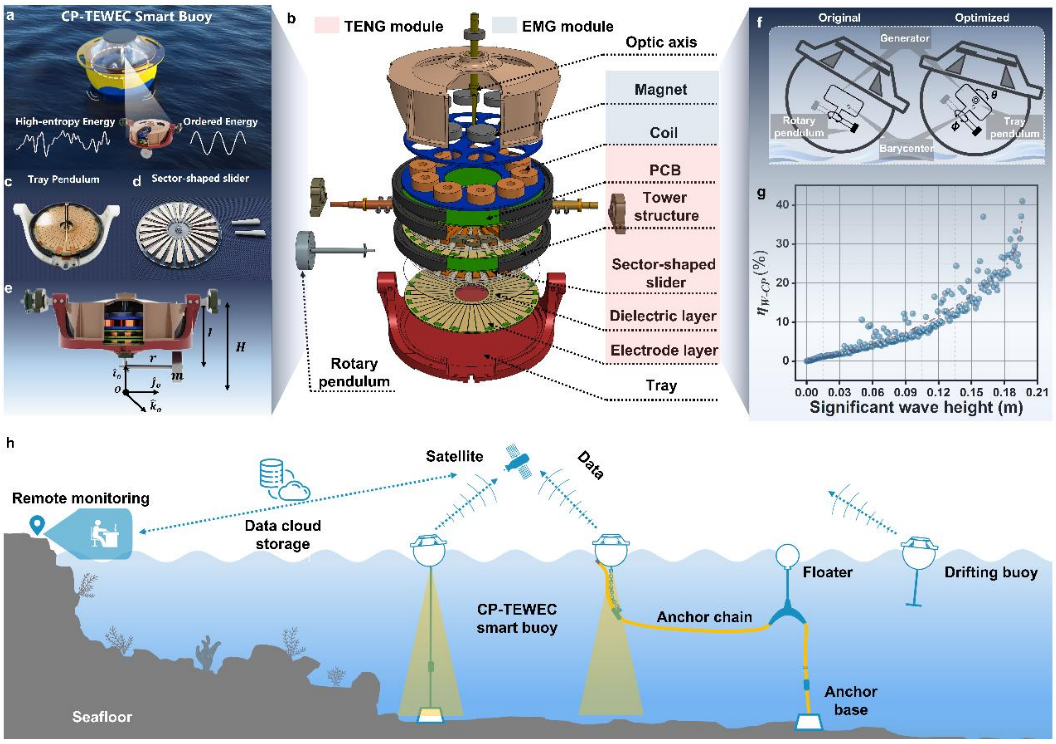


Fig. 1 Application scenario and scheme design of the CP-TEWEC.

8- Please check if you have a typo (hollow box) in Equations N2-5 and -6. Verify also if Equations N2-1 and -2 are correctly written, as they seem slightly different from the reference I usually resort to for verification (Handbook of Ocean Wave Energy, page 56). In page 59 of this document, you should also verify the definition of the ratios between Tp and Te, which you designate as a "shape" parameter in N2-7. Confirm also if what you are defining in Equation N2-8 is the Capture Width Ratio metric (CWR) commonly used in WEC design;

Author response:

1. Typo in Equations N2-5 and N2-6

We have carefully reviewed equations N2-5 and N2-6 and confirmed that no typographical errors related to the term "hollow box" were found in these equations. We are uncertain whether the term "hollow box" is a result of incorrect symbol rendering in the formula editor.

2. Regarding the notation of equations N2-1 and N2-2

We have cross-checked the notation of these equations and observed that it differs from the expression found on page 56 of the *Handbook of Ocean Wave Energy*. Our intention was to identify a formula that is solely related to significant wave height and spectral peak period, facilitating the quantification and comparison of numerical calculations with experimental results. We have also reviewed the formula symbols in the Supplementary Note 3 and included relevant references (*Random seas and design of maritime structures*) for the formulas, which can be found on page 29.

Revised Text:

Accordingly, the JONSWAP spectrum is chosen to establish the numerical model, as defined by the following function[1],

$$S(\omega)=\beta_J\frac{H_s^2}{T_p^4\omega^5}\exp[-\frac{5}{4}(\frac{1}{T_p\omega})^4]\gamma^{\exp[-\frac{(T_p\omega-1)^2}{2\sigma_s^2}]} \quad \text{(N3-1)}$$

$$\beta_J=\frac{0.0624}{0.230+0.0336\gamma-\frac{0.185}{(1.9+\gamma)}}[1.094-0.01915\ln\gamma],\ \gamma\in[1,7] \quad \text{(N3-2)}$$

3. Regarding the definitions of T_p and T_e (Equation N2-7)

We have noted the issue raised by the reviewer and have re-examined the definition based on the description provided on page 59 of the *Handbook of Ocean Wave Energy*. The clarification has been incorporated into the revised manuscript.

Revised Text:

"Here, σ is derived from empirical formulas ($1.12T_e = T_P$), with $\sigma = 0.9$ for irregular wave spectra characterized by the JONSWAP spectrum."

4. Regarding the capture width ratio in Equation N2-8

We confirm that the definition given in Equation N2-8 differs from the commonly used capture width ratio (CWR) in conventional WEC designs. According to the marine energy standard IEC/TS 62600-1: 2019, Marine Energy - Wave, Tidal and Other Water Current Converters, Part 1: Terminology, issued by the International Electrotechnical Commission (IEC), the capture width ratio (CWR) is defined as the ratio of the mechanical energy captured by a WEC in its first stage to the wave power input within the characteristic width of the device. However, under the decoupled mechanism, our primary interest lies in understanding the energy conversion efficiency of the chaotic pendulum-based energy capture system under various wave conditions. Therefore, we have introduced a new energy conversion metric for this system, analogous to the conventional capture width ratio.

Reference

1. Goda, Y. *Random Seas and Design of Maritime Structures*. vol. Volume 15 (WORLD SCIENTIFIC, 2000).
2. *Handbook of Ocean Wave Energy*. vol. 7 (Springer International Publishing, Cham, 2017).

9- Line 146: could you clarify the reason for this outcome of the magnetic flux intensity? A similar clarification would be appreciated with regards to Line 181's remark, by comparison with what is discussed in reference 60 after Equation 2c;

Author response:

We sincerely appreciate the reviewers' valuable suggestions. We have carefully reviewed the content in lines 146 and 181 and have provided further clarifications on these two issues.

Regarding the results of magnetic flux intensity in line 146:

The magnetic flux density results presented in the manuscript are primarily influenced by the magnetic field distribution within the electromagnetic generator, the conductor's motion velocity, and their relative positioning. To enhance the clarity of this explanation, we will supplement the manuscript with details on the COMSOL simulation process, illustrating how the magnetic flux density values were computed. These additions will provide a more comprehensive understanding of the factors governing the variations in magnetic flux density observed in our study.

Regarding the impact of electrostatic adhesion force on TENG in line 181:

Revised Text (lines 228-237):

During stator-rotor relative rotation, electrostatic adhesion forces inevitably introduce additional resistance to the motion of the sector-shaped sliding blocks. To minimize energy dissipation, we optimized the slider mass to balance triboelectric contact pressure while mitigating inertial and frictional losses. Energy loss arises from microscale interfacial friction, inducing asperity deformation, lattice dislocations, and phonon-mediated thermal dissipation. Eq. (1-4) reveals that the electrostatic adhesion force is rotationally invariant, governed exclusively by the dielectric material's charge density (σ), interfacial geometry (r_1, r_2), and intrinsic triboelectric properties. Further, the coreless EMG module further enhances low-speed energy harvesting via a contactless design, eliminating mechanical wear and eddy current losses. These clarifications have been incorporated into the revised manuscript to ensure a more precise discussion of the underlying physical processes.

10- Figures and Tables should appear right after they are first cited in the text (for instance, correct this in Figure 3);

Author response:

Thank you for your suggestion regarding the order of figure and table citations. We fully understand that figures and tables should appear in the manuscript immediately after they are first mentioned in the text. In the revised manuscript, we will adjust their placement accordingly to ensure they are presented in the proper sequence.

11- Table S1: were these values measured in the physical model of the device, or obtained under the specific condition of a maximum static friction force of 3.5 N? Please clarify, as well, whether you are working with model or prototype values, particularly when you define parameters such as the rotating pendulum's weight;

Author response: Thank you for your detailed inquiry regarding Table S1 and the parameter definitions. In response to the reviewer's suggestions, we would like to clarify the following points:

Physical Model and Static Friction Condition:

The values presented in Table S1 are derived from both the physical model and numerical calculations.

Distinction Between Model and Prototype:

During both the tank and sea trials, we conducted tests using a 1:1 scale prototype, meaning the parameters listed in Table S1 correspond to the full-scale system.

To ensure clarity, we will add a statement in the manuscript explicitly defining the scale of these parameters.

Revised Text:

In the experiments, a full-scale (1:1) prototype was used to ensure the experimental conditions closely resemble real-world marine environments. All structural parameters, including dimensions, mass distribution, and hydrodynamic properties, were maintained identical to those of the actual deployed system. This approach eliminates scale effects that may arise in reduced-scale models, ensuring that the experimental results accurately reflect the device's real-world performance. The measured parameters in this study, such as wave-induced motion, power generation efficiency, and structural stability, therefore correspond directly to the full-scale system.

12- Please check if Figure S4 has a correct caption, as in both a) and b) you present current and charge results. If I interpreted it correctly, b) is a zoom of a), but please confirm;

Author response: Thank you for your attention to the caption of Figure S4.

Based on your description, both (a) and (b) in Figure S4 indeed present current and charge results, with (b) being a magnified view of (a). In the revised manuscript, we clarify this in the caption of Figure S4 to ensure consistency between the figure description and its actual content. If there are any other ambiguities, we will further refine the figure and its explanation to ensure clear and accurate presentation of the research results.

Revised Figure:

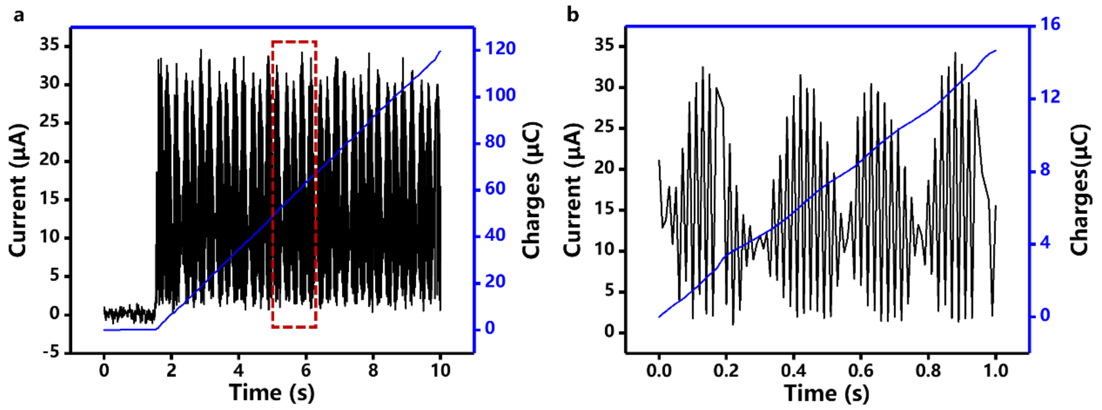


Figure S1 **a** The current and charge of TENG module measured by using DB107 circuit at a speed of 60 rpm. **b** A zoomed-in view of the data presented in red box.

13- Line 354: could you please clarify if the 24 sectors account for all of the outer diameter of the device (7º times 24º is equal to 168º, under 360º, and 52.5 times 7º converted to radians is equal to about 154 mm, slightly above 150 mm)? Also, in Line 393, did you use a specific type of commercial buoy as a reference to define your model, or was the model constructed without a specific reference?

Author response: Thank you for your attention to the structural details of the device.

Regarding the reviewer's question on Line 354 about the sector coverage angle, we would like to clarify the definition of a sector.

The 24 sectors in the device actually refer to the number of electrode pairs, with each sector consisting of two interdigitated metallic electrodes, resulting in a total of 48 fan-shaped electrodes. Each fan-shaped electrode spans 7°, with an inter-electrode gap of 0.5°, ensuring that all electrodes fully cover the PCB board.

Since the concept of sectors may have caused some misunderstanding, we will provide a clearer explanation of the relationship between sectors and electrodes in the revised manuscript, along with a more detailed structural description to avoid similar confusion.

Revised Text:

The outer rotor has an outer diameter of 150 mm and an inner diameter of 8 mm. It consists of 48 fan-shaped electrodes, grouped into 24 electrode pairs (sectors), each spanning 7° with an inter-electrode gap of 0.5°. The corresponding chord length for each electrode is 52.5 mm, ensuring full 360° coverage around the rotor.

Source of reference for buoy prototype

We adopted the buoy's external structural characteristics from the www.spoondrift.co. However, the design, dimensions, and mass of its internal dynamic components were determined through dynamic analysis and parameter optimization.

Reviewer #3 (Remarks to the Author):

This study presents a chaotic-pendulum wave energy harvesting buoy based on a triboelectric-electromagnetic hybrid nanogenerator. The chaotic pendulum decouples the floater-generator motion, converting irregular wave energy into steady power and maintaining buoy equilibrium in marine environments. This work can be useful for small scale ocean energy harvesting, I recommended this paper for major revision.

environments.

1. What are the primary advantages of this work compared to state-of-the-art small-scale wave energy converters utilizing conventional electromagnetic generators (EMGs)?

Author response: Thank you very much for raising this concern.

The CP-TEWEC developed in this study demonstrates four principal advantages over conventional electromagnetic generator (EMG)-based wave energy harvesters for marine monitoring buoy applications:

(1) Centroid Stability

The tray pendulum configuration fundamentally resolves eccentric mass distribution issues in miniaturized rotational systems by maintaining geometric symmetry during operation. This dual achievement of compact dimensions and mechanical reliability ensures stable power delivery for onboard instrumentation.

(2) Spatial Efficiency

Integration of rotational generators within the pendulum architecture optimizes internal space utilization, while the hybrid TENG-EMG configuration achieves enhanced power density through synergistic energy harvesting (see Figure 4h).

(3) Spectral Adaptability

The system combines the pendulum's low-frequency excitation sensitivity characteristics with advantages of TENG's low-frequency energy harvesting, complemented by EMG's high-frequency responsiveness, enabling broadband energy harvesting across varying marine conditions.

(4) Deployment Scalability

Featuring simplified mechanical architecture and modular construction, the design enables cost-effective mass production and distributed deployment, which is critical requirements for large-scale ocean monitoring networks.

2. What is the total energy conversion efficiency of the proposed system, from wave energy to electricity? How does this efficiency compare with state-of-the-art hybrid TENG systems or small-scale wave energy converters using conventional EMGs?

Author response: Thank you very much for raising this concern.

Revised in Supplementary Note 6:

To compare the energy conversion efficiency from wave energy to electrical energy of small wave energy converters of different sizes, a method for calculating energy conversion efficiency was first established. For devices subjected to regular wave excitation, the wave energy flux is calculated using the following formula,

$$W_r = \frac{1}{2}\rho g H^2 c_g$$

$$c_g = \frac{1}{2}c\left(\frac{2kd}{\sinh 2kd} + 1\right)$$

Here, H represents the wave height, c_g denotes the group velocity of wave energy propagation, c is the phase velocity, k is the wave number, and d is the water depth. For devices subjected to irregular wave excitation, the wave energy flux is calculated using the following formula,

$$W_{wn} = \frac{\rho g^2 H_s^2 T_E}{64\pi}$$

Here, H_s represents the significant wave height, and T_E denotes the energy period. According to the JONSWAP spectrum, $T_E = 0.9T_P$, where T_P represents the peak period of the irregular waves. Finally, the energy conversion efficiency is calculated using the given formula,

$$\eta_{regular} = \frac{W_e}{W_r B}, \quad \eta_{irregular} = \frac{W_e}{W_{wn} B}$$

Here, W_e represents the final electrical energy output of the device, and B denotes the characteristic width of the device. After calculations, the energy conversion efficiency of the proposed CP-TEWEC is determined to be 5.21 %. To provide a clear comparison, Table N2 presents the energy conversion efficiencies of various advanced small-scale wave energy harvesting devices with different structural types in recent years. As shown, the proposed device demonstrates a competitive advantage.

Table N1 Comparison of energy conversion efficiency of small-scale WECs.

Reference	**Year**	**Structure Type**	**Wave**	***H* (m)**	***T* (s)**	**Output**	***B* (m)**	**η (%)**
This Paper	2024	Chaotic Pendulum	Random Wave	0.12	1.92	0.27 W	0.43	5.21
1	2019	Attenuator	Regular Wave	0.1	1	4.5 mW	0.14	0.335
2	2020	Horizontal axis Pendulum	Regular Wave	0.14	0.5	1.23 mW	0.1	0.131
19	2020	Horizontal axis Pendulum	Random Wave	1.42	3.45	2.5 mW	0.1	0.000816
20	2021	Double-mass pendulum	Regular Wave	0.1	0.7	0.1 W	0.4	3.74
21	2021	Spring-mass	Regular Wave	0.15	4	1 W	0.4	3.34
22	2022	Mass	Random Wave	2	6.28	0.13 W	0.5	0.00238
23	2022	Spring-mass	Regular Wave	0.1	1	81 mW	0.25	3.37
4	2022	Horizontal axis Pendulum	Regular Wave	0.12	0.71	48.8 mW	0.15	3.31
8	2022	Horizontal axis Pendulum	Regular Wave	0.05	1	0.7 mW	0.08	0.364
17	2023	Attenuator	Regular Wave	0.16	2	0.74 W	0.4	3.15
24	2023	Gyroscope	Random Wave	2	7.5	138.56 W	0.4	2.66
25	2024	Mass	Regular Wave	0.32	2.5	6.4 W	0.6	3.80
26	2024	Mass	Regular Wave	0.9	3.9	5.7 W	1.08	0.197

3. Given that hybrid systems have greater complexity than standalone TENG systems, which increases the risk of system failure, how does this design address potential reliability issues?

Author response: Thank you very much for raising this concern. We mainly adopt the following four measures to solve potential reliability problems:

(1) Friction Optimization

Optimized material selection for dielectric layers and sliding components minimizes rotational torque requirements, effectively reducing mechanical wear for sustained operation. The PVC dielectric maintains robust power generation performance even after one million friction cycles, while the lightweight PLA slider (1.5g) ensures minimal inertial friction losses.

(2) Modular Power Architecture

Independent energy conversion channels with dedicated power management circuits ensure operational stability. An acrylic structure is used to achieve physical isolation between TENG and EMG, and power output is carried out through parallel connection, which ensures the independence of the two and the stability of energy output.

(3) Survivability assurance

Multi-level protective measures including hermetic sealing, resonant frequency modulation via mass distribution adjustment, and pendulum motion limiters enhance survivability in extreme wave conditions.

(4) Condition Monitoring Integration

An embedded condition monitoring system tracks critical parameters through angular velocity/displacement sensors on rotating assemblies, enabling predictive maintenance and real-time operational diagnostics.

4. How does the output power of the LTC3588 circuit compare when using only an EMG versus a hybrid configuration combining TENG and EMG? Specifically, is there a significant power loss in the energy management process when the outputs of TENG and EMG are combined without impedance matching?

Author response: Thank you very much for raising this concern. We acknowledge an illustration error in our initial documentation. The energy management configuration specifically employs the LTC3588 circuit exclusively for the EMG module, while implementing charge excitation circuitry for the TENG component. The corrected schematic representation is provided in the revised figure.

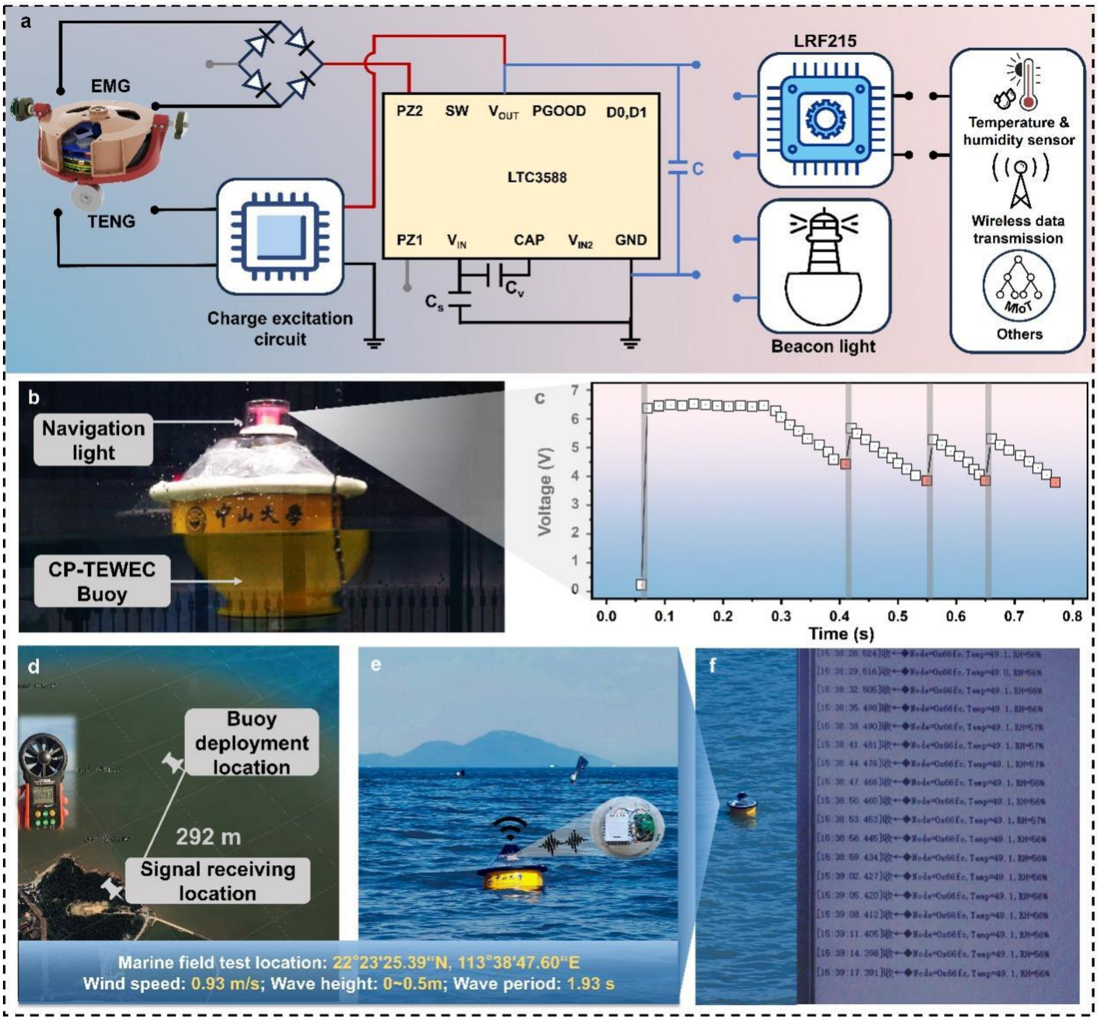


Fig. 5 Application demonstration of the CP-TEWEC buoy.

Reference

1. Wang J*, et al.* Rational structure optimized hybrid nanogenerator for highly efficient water wave energy harvesting. *Adv. Energy Mater.* **9**, 1802892 (2019).
2. Chen X*, et al.* A chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator for wave energy scavenging and self-powered wireless sensing system. *Nano Energy* **69**, 104440 (2020).
4. Han C*, et al.* Hybrid triboelectric-electromagnetic nanogenerator with a double-sided fluff and double halbach array for wave energy harvesting. *Adv. Funct. Mater.* **32**, 2205011 (2022).
8. Zhang Y*, et al.* Multi-purpose triboelectric-electromagnetic hybrid nanogenerator with a mechanical motion-controlled switch for harvesting low-frequency energy. *Nano Energy* **104**, 107867 (2022).
17. Chen W*, et al.* Design and experiment of a double-wing wave energy converter. *Renew. Energ.* **202**, 1497-1506 (2023).
19. Carandell, M., Toma, D. M., Carbonell, M., del Rio, J. & Gasulla, M. Design and testing of a kinetic energy harvester embedded into an oceanic drifter. *IEEE Sens. J.* **20**, 13930–13939 (2020).
20. Cai, Q. & Zhu, S. Applying double-mass pendulum oscillator with tunable ultra-low frequency in wave energy converters. *Appl. Energy* **298**, 117228 (2021).
21. Li, M. & Jing, X. A bistable X-structured electromagnetic wave energy converter with a novel mechanical-motion-rectifier: design, analysis, and experimental tests. *Energy Convers. Manag.* **244**, 114466 (2021).
22. Harms, J., Hollm, M., Dostal, L., Kern, T. A. & Seifried, R. Design and optimization of a wave energy converter for drifting sensor platforms in realistic ocean waves. *Appl. Energy* **321**, 119303 (2022).
23. Vella, N. *et al.* A modular wave energy converter for observational and navigational buoys. *Fluids* **7**, 88 (2022).
24. Zhang, Y. *et al.* Gyroscopic wave energy converter with a self-accelerating rotor in WEC-glider. *Ocean Eng.* **273**, 113819 (2023).
25. Everett, J., Sorokin, V., Whittaker, C. & Aw, K. Numerical and experimental analysis of the power output performance of a point absorber WEC for nearshore wave conditions. *Ocean Eng.* **309**, 118381 (2024).
26. Chen, X., Lu, Y., Zhou, S. & Chen, W. Design, modeling and performance analysis of a deformable double-float wave energy converter for AUVs. *Energy* **292**, 130533 (2024).

Responses to Editor and Reviewers

Manuscript number: No. NCOMMS-24-75130A

Title: A Pendulum-based Nanogenerator for High-Entropy Wave Energy Harvesting

Authors: Tiancong Zhao[1, 2, †], Zhengyu Li[1, †], Bo Niu[1, †], Guangci Xie[1], Liang Shangguan[1], Meikun Zhang[1], Yurun Zhu[1], Yong Ma[1, 3, *], Chao Hu[1, *] and Ying Li[2, *]

We sincerely appreciate the Editor's preliminary acceptance decision and the reviewers' constructive comments on our manuscript entitled "[A Pendulum-based Nanogenerator for High-Entropy Wave Energy Harvesting]" (Manuscript ID: [No. NCOMMS-24-75130A]). We are particularly grateful to Reviewer 2 for their final insightful suggestions, which have further strengthened our work.

In this revised version, we have meticulously addressed all remaining points following the journal's formatting guidelines. Below we provide point-by-point responses to Reviewer 2's comments, with:

Reviewer's original text in green

Our responses in black (marked "Response:")

Reviewer #1 (Remarks to the Author):

The authors addressed all the comments raised by the reviewers. So I recommend the paper to be accepted by Nature Communications.

Author response:

We sincerely appreciate your thorough evaluation and supportive recommendation for acceptance. We are grateful for the constructive feedback provided during the review process, which has significantly improved our manuscript.

Reviewer #2 (Remarks to the Author):

The paper proposes a chaotic pendulum triboelectric-electromagnetic hybrid nanogenerator-based wave energy converter (CP-TEWEC) for marine equipment powering applications. The mechanism seeks to hybridize a rotary double-pendulum TENG with a standard EMG, in order to promote operational synergies and enhance energy harvesting from low frequency, low amplitude ocean wave action. An experimental study was conducted to demonstrate the proposed device, namely for supplying a self-powered marine temperature and humidity sensing system.

The authors underwent significant efforts towards improving the paper, based on the reviewrs' comments. This is highly appreciated and has been reflected upon the enhancement of the work's quality. On my part, I am willing to recommend an acceptance of the paper in general. However, I would like the authors to explain a bit better their responses to my Major Comments #8 and #11. My doubts relate to the wave conditions and the scale of the wave tank experiments:

Comments:

i) the authors state that the scale of the experiment was 1:1, but in the wave flume the wave conditions seem to refer to values at a reduced scale. While the buoy itself may conserve its full-scale size, the wave conditions should also be equivalent to those at sea. Either both are at reduced scale or full-scale, but not a combination of either. The duration of the experiments with irregular waves also seems limited, as I am used to seeing works with 512 or more waves being generated per cycle for an adequate sweep of the wave spectrum;

ii) the authors should clarify better what are the local wave conditions and what is the original dataset from which the data was extracted. A wave rose or historical time series Figure would assist in this matter, for instance.

Author response: Thank you very much for raising this concern.

The problem of experimental scale and wave scale

The buoy and pendulum system were tested at full scale (1:1), as they are designed for small-scale marine monitoring applications. However, due to wave flume constraints, the wave heights were adjusted to match the energy content of typical ocean waves while preserving the spectral characteristics (e.g., JONSWAP γ =3.3) and peak periods derived from Zhuhai coastal data. This approach ensures dynamic similarity in terms of nonlinear pendulum response, even if wave heights differ from open-sea conditions.

Supplement wave data

Wave Conditions: The wave parameters (H_s = 0.18 ~ 0.66 m, T_p = 1.8 ~ 4 s) were derived from tide table database (2024.1~2024.6) for Zhuhai's nearshore zone (depth ~15 m, 3 nautical miles around the island). While these values are smaller than open-ocean conditions, they represent realistic local operational environments for small marine sensors.

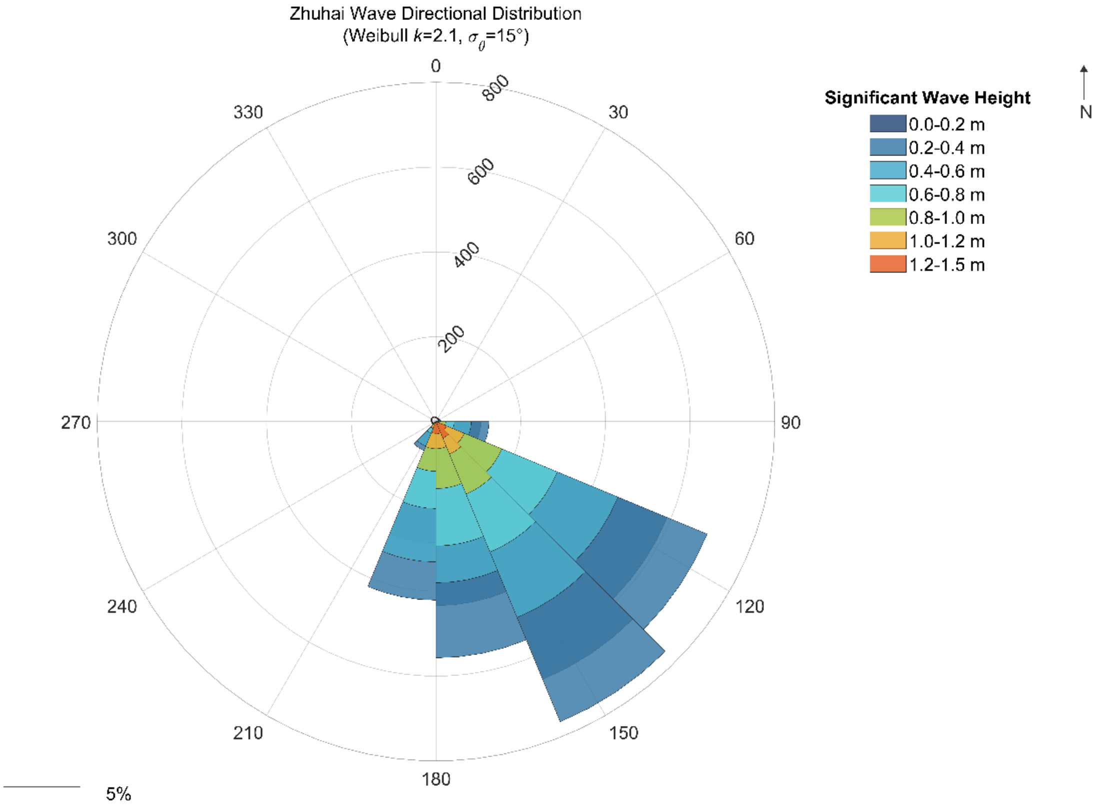


Figure 1 Wave rose chart of Zhuhai Sea area in China.

Irregular wave duration

We appreciate the reviewer's insightful comment regarding the duration of irregular wave testing. While 512 waves per cycle is indeed common for open-ocean spectral characterization, our experimental design was carefully optimized for device performance testing in constrained wave flume conditions through the following considerations:

Physical Constraints & Signal Integrity

The wave flume's effective length (75 m) and wavemaker stroke limit impose practical constraints. Prolonged wave generation (>200 waves in our tests) would introduce—— Significant superposition effects from reflected waves at the distal end. (Reflection coefficients exceed 15% after 200 waves). These effects are negligible within our 150-wave duration (reflection <3%)

Standards Compliance

The experimental procedure follows ITTC Recommended Procedures for Wave Energy Converter Testing (2021). We meet and exceed the ITTC 2021 minimum requirement (100 waves)

Device Response Convergence

Further, we conducted a rigorous power-output convergence analysis to validate the experimental duration, demonstrating that 150 irregular waves provide statistically robust characterization of the buoy-pendulum dynamics. Figure 2 shows the mechanical power output (calculated from angular velocity) reached 95% stability at 105 waves.

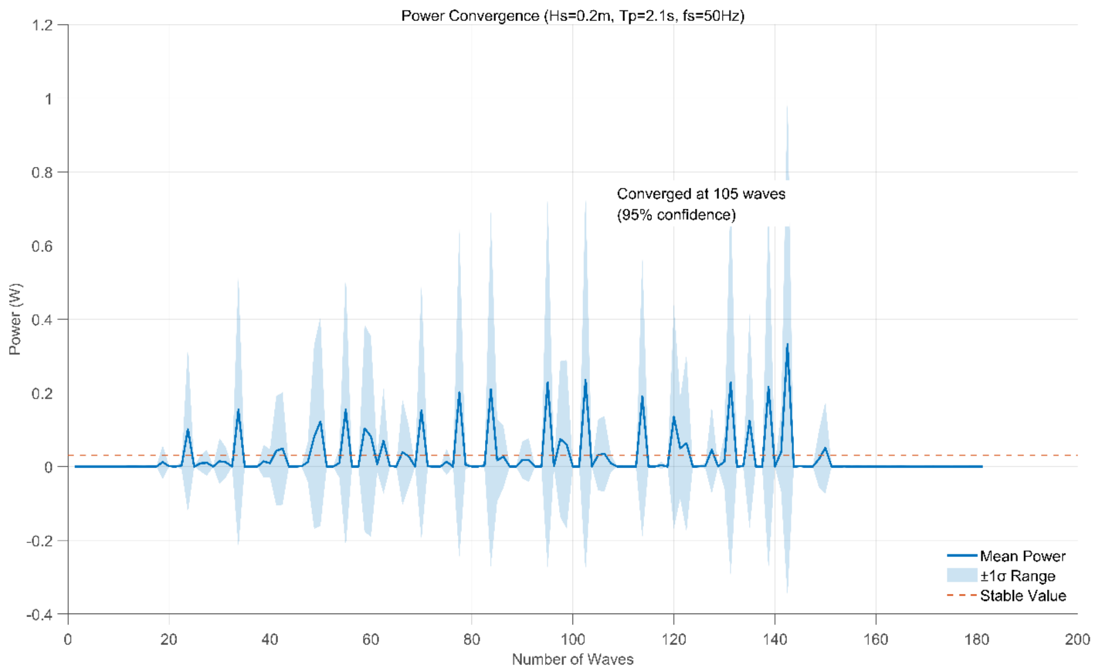


Figure 2 Stabilization of mechanical power output under irregular wave excitation.

Forward-Looking Improvements

The current tests focused on performance validation under representative conditions, but our next-phase experiments will:

a) Incorporate 500+ wave cycles in a new ocean basin facility (under construction)

b) Include multi-directional waves matching full spectral widths

c) Benchmark against open-ocean data from the South China Sea buoy network

Reviewer #3 (Remarks to the Author):

Authors answer all my comments. I recommend this paper for publication

Author response: We thank Reviewer 3 for their time and valuable feedback, as well as their positive recommendation for publication. We are pleased that our revisions adequately addressed their comments, and we appreciate their support for our work.