Harnessing ocean thermal-salinity-pressure gradients for offshore energy battery clusters

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Dear Editor,

Ocean thermal energy (OTE) and salinity gradient energy (SGE) systems face critical limitations in energy density and operational continuity due to fragmented exploitation of oceanic energy gradients. Phase Change Material (PCM) equipped thermal underwater gliders, through buoyancy regulation, enable the coupled conversion of thermal energy, pressure energy, and salinity gradient energy, along with an elevation in energy grade. This approach shows promise as a breakthrough technology for synergistic OTE-SGE exploitation. However, current research on OTE, SGE, and thermal underwater gliders remains fragmented and independent: OTE studies focus primarily on enhancing thermal efficiency under limited temperature differentials; SGE research concentrates on developing high-efficiency ion-exchange membranes for salinity gradient conversion; while thermal underwater gliders' energy output is still confined to propulsion functions. To date, no systematic framework integrating these technologies has emerged. The proposed system operates as a dynamic 'energy glider': descending via PCM solidification to concentrate brine under hydrostatic pressure, and converting amplified salt differentials into electricity through reverse electrodialysis (RED). This integration bypasses traditional pumps and turbines, offering a scalable solution for offshore energy autonomy.

INTRODUCTION

OTE[1] and SGE[2] represent distinct categories of marine renewable energy. Their fundamental similarity lies in harnessing energy from spatial gradients of physical properties, to be specifically, temperature gradients for OTE and salinity gradients for SGE. Owing to their vast reserves, both hold significant development potential. However, the exceptionally low magnitude of these gradients results in critically low energy density. Developing these resources carries substantial economic viability risks, where operational costs may outweigh energy output. The low energy grade of OTE and salinity gradient energy creates substantial economic viability risks in their development, where operational costs may outweigh energy output. Another critical constraint on SGE utilization stems from the need to deploy equipment at river estuaries to capture sufficient salinity gradients. The position of the freshwater-seawater interface is highly susceptible to tidal fluctuations, imposing significant constraints on conversion stability. These cost-effectiveness barriers represent the fundamental constraint hindering technological progress. In this letter, we propose a conceptual framework for an integrated marine energy system centered on salinity gradient batteries (SGBs), synergistically enhanced by thermal phase-change actuation and pressure-driven salt concentration. By converting oceanic thermal gradients into mechanical buoyancy cycles, amplifying salinity differences via reverse osmosis (RO), and storing energy through closed-loop electrochemical SGBs, the system theoretically achieves a cascaded energy conversion chain. This work pioneers the synergistic exploitation of thermal, salinity, and pressure gradients simultaneously through cascaded energy conversion. Distinct from static installations, we further introduce mobile, self-optimizing battery clusters. These clusters dynamically adapt to oceanic gradients and operational demands, enabling scalability and resilience for deep-sea applications. This design aims to overcome the limitations of natural salinity gradients while providing a scalable blueprint for offshore energy storage and resilience, aligning with global decarbonization goals.

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THERMO-SALINO-PIEZOELECTRIC CONVERSION MECHANISMS

The proposed system integrates three synergistic mechanisms—thermal-driven buoyancy cycling, pressure-enhanced salinity amplification, and salinity gradient energy conversion—into a seamless energy cascade. The schematic diagram of the energy platform can be seen in Figure 1. Below, we elaborate on each mechanism's operational principles, material implementations, and quantitative foundations.

Thermal-Powered Buoyancy Cycling

One of the cores the system lies the exploitation of oceanic thermal gradients to drive vertical motion through PCMs based thermal underwater glider[3]. Ocean thermal gradients between sunlit surface waters and cold deep layers drive cyclical phase transitions in encapsulated materials, converting heat into vertical mechanical motion. The density difference between the PCM and seawater generates buoyancy forces for ascent and descent. Take the Paraffin-based microencapsulated PCMs[4] as an example, such as paraffin-$CaCO_3$ composites, are housed in pressure-tolerant titanium capsules. When exposed to surface seawater temperatures (~28°C)[5], the PCM absorbs latent heat (210 kJ/kg), transitioning from solid to liquid and expanding volumetrically by 14%. This expansion reduces the capsule's density, generating buoyant force to ascend. Upon reaching the surface and completing a predefined mission phase, an active buoyancy control system is engaged. When sinking is required, a command is sent to a pump, which contracts an internal oil bladder, slightly reducing the glider's overall volume. This critical action disrupts the buoyant equilibrium, initiating a controlled descent. As the glider then descends into colder depths, the PCM releases its latent heat and undergoes solidification, contracting and further increasing its density. This phase transition amplifies the sinking force, ensuring a continuous descent to the target depth. This cyclical phase change—melting for ascent and solidifying for descent—is the core mechanism that enables the glider's perpetual vertical motion, harnessing the ocean's thermal gradient as its engine.

Pressure-Driven Salinity Amplification

A major innovation of this study is the glider-based SGB clusters, designed to convert deep-sea hydrostatic pressure into electrical energy via pressure differentials. As the gliders descend, hydrostatic pressure of 0-10MPa at depth of 0-1000 m is harnessed to mechanically concentrate seawater via RO[6]. Thin-film composite membranes are housed in pressure-tolerant chambers[7], where incoming seawater is forced through the membrane. Under high pressure, RO membranes force water molecules through the membrane while retaining salt, thereby separating seawater into two streams: low-salinity permeate and high-salinity concentrate. By cycling this process, the salinity of the seawater can be continuously increased, enhancing the salinity gradient. The RO membrane components are enclosed in a rigid, pressure-resistant chamber. One side of the chamber is equipped with a filtration port, approximately 1-5 micrometers in pore size, which allows seawater to enter. The opposite side is connected to a high-salinity storage tank. The RO membranes are arranged in a spiral or flat configuration, with flow-directing grids separating the membrane layers to create a distinct high-pressure feed

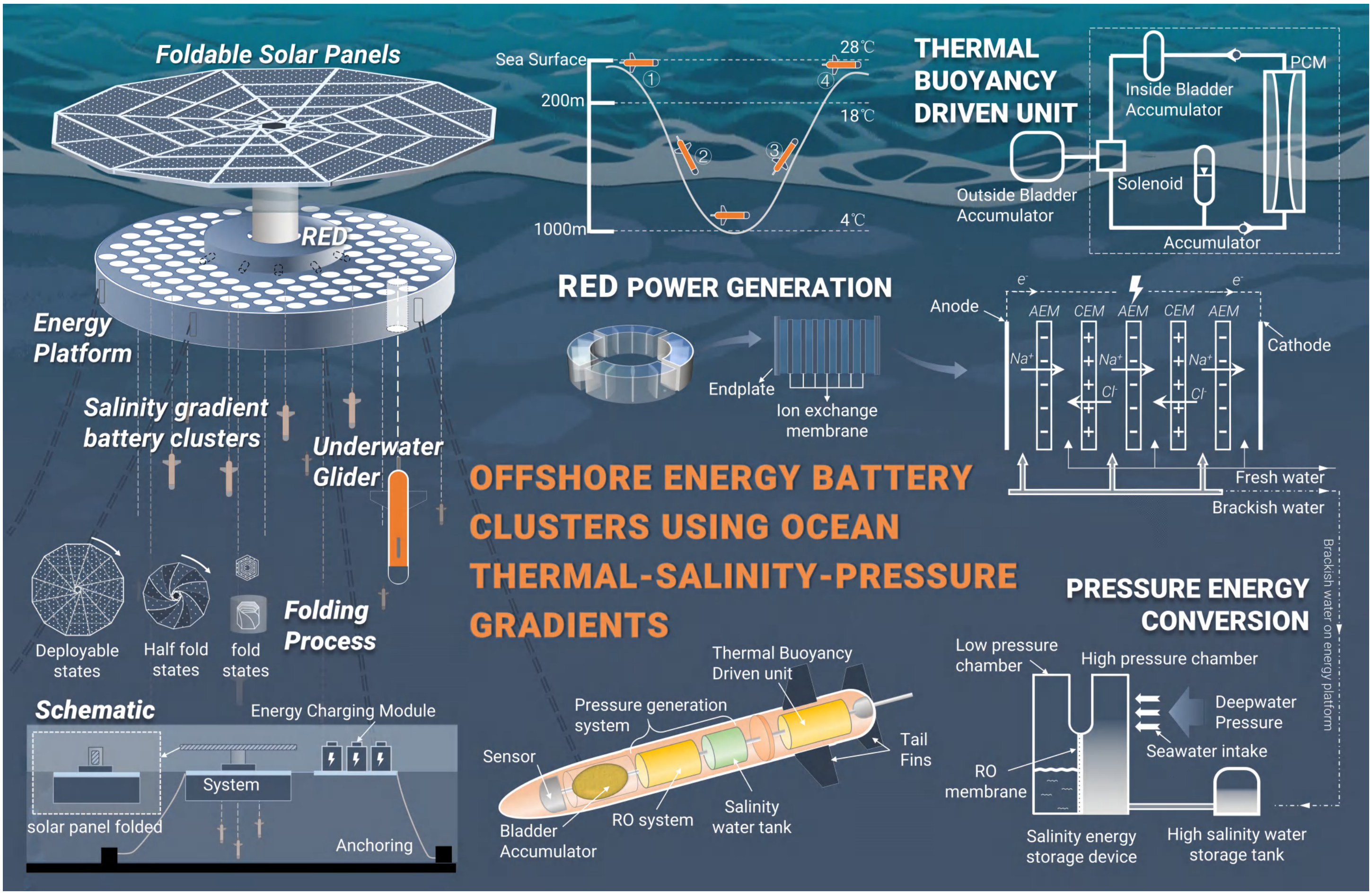

Figure 1. The schematic diagram of offshore energy battery clusters using ocean thermal-salinity-pressure gradients

side and a low-pressure product side. As the device descends, external water pressure is transmitted through the filtration port into the chamber, forcing seawater into the high-pressure side. Under the influence of the osmotic pressure differential, freshwater passes through the RO membrane into the low-pressure side, while salt is retained, and the concentrated brine is collected in the storage tank, which is stored for subsequent energy conversion. In fact, seawater with an initial salinity of 35 psu can be concentrated to 50 psu, effectively tripling the salinity gradient (ΔS) compared to ambient seawater. This process leverages the ocean's own pressure to amplify energy potential without energy-intensive pumping.

Salinity Gradient Energy Conversion via Reverse Electrodialysis

The high-salt water flow concentrated by RO is directly pumped into the high-salt flow channel of RED[8] in surface module, and the low-salt water flow is taken from the surface seawater. The amplified ΔS drives RED, where alternating cation and anion exchange membranes separate high and low salinity streams. Sodium and chloride ions migrate across the membranes, generating an ionic current captured by electrodes. The resulting electrical output scales with ΔS, enabling power densities up to 3 W/m^2 for gradients exceeding 40 psu. Excess energy is stored in SGB, which utilize the same salt differentials to reversibly charge and discharge through redox reactions.

DESIGN AND DEPLOYMENT STRATEGY

The system is structured as a vertically stratified, modular unit optimized for deployment in subtropical and tropical oceans, where thermal and salinity gradients[9] are most pronounced. The surface module incorporates foldable solar photovoltaic panels to supply essential power for system communication and control. Crucially, these foldable panels enable the module to submerge, thereby mitigating adverse impacts from extreme weather conditions such as storms and high waves. Additionally, this module integrates concentrated brine storage tanks to collect high-salinity brine harvested by thermal underwater gliders. Finally, it houses RED stacks and SGB clusters, where electrochemical energy conversion and storage occur. Short-term energy fluctuations are buffered by the SGB, which store energy in ion-concentration cells exhibiting minimal self-discharge. The deep-layer modules primarily consist of thermal underwater gliders based SGB clusters. These integrate RO membranes and flow channels to concentrate brine under ambient hydrostatic pressure. This configuration facilitates depth cycling (sinking and rising) driven by thermal gradients and enables the conversion of pressure energy into salinity gradient energy. Deployment prioritize regions with stable thermoclines, to synchronize thermal cycling with natural oceanic rhythms.

The three mechanisms form a closed-loop cycle: thermal energy drives buoyancy adjustment via PCM within the thermal underwater gliders, whose density changes induce cyclical sinking and rising; hydrostatic pressure facilitates salinity amplification as the gliders utilize ambient pressure and RO membrane permeability to concentrate brine, converting pressure into salinity gradient energy; and electrochemical conversion harvests electricity within the surface module. This final process powers system communications, houses the gliders, stores their harvested concentrated brine, generates electricity using RED, and buffers fluctuations via SGB clusters.

The key difference from traditional thermal underwater gliders lies in the fact that the system proposed in this study utilizes temperature differences solely to facilitate the glider's descent and ascent, without directly participating in energy conversion. Instead, the system's pressure energy is derived from the pressure difference between the sea surface and deep water. This approach ensures that the temperature-driven energy is harnessed to alter the glider's buoyancy, enabling vertical movement, while the pressure energy is generated through hydrostatic pressure gradients. This design contrasts with systems where temperature differences are directly converted into mechanical energy via phase change materials to drive the glider. In this proposed system, the temperature gradient serves as a passive mechanism for adjusting buoyancy, whereas the pressure energy is actively extracted from the hydrostatic pressure differential, offering a distinct operational strategy.

System-level efficiency of 29% emerges from cascading efficiencies: 65% mechanical-to-chemical via RO based pressure-driven salinity amplification, and 45% chemical-to-electrical via RED based salinity gradient energy conversion.

The energy conversion from salinity gradients is governed by the equation:

$$\pi_i = kC_i \tag{1}$$

$$C_i = \frac{C_0 V_{i,0}}{V_{i,0} - \Delta V} \tag{2}$$

$$\Delta C = \frac{\Delta P}{k} = \frac{\Delta \pi_i}{k} \tag{3}$$

$$E_{salt} = \int_0^{\Delta V} \Delta \pi dV \tag{4}$$

where $\Delta\pi_i$ is the osmotic pressure difference, k is the osmotic pressure constant, ΔP is the hydrostatic pressure difference between depth and sea level, C_0 is the initial seawater concentration, C_i is the final salinity on the feed/permeate side, $V_{i,0}$ is the initial volume on the feed/permeate side, ΔV is the volume of migrated water, and E_{salt} is the total salinity gradient energy.

Based on this equation, a single thermal underwater glider (500 mm diameter, 6 m length) operating at 0.2 m/s yields daily power outputs of 2.89 kWh, 4.08 kWh, 4.23 kWh, and 3.51 kWh at depths of 250 m, 500 m, 1000 m, and 2000 m, respectively. An array of just 100 such gliders would therefore generate between 289 and 423 kWh/day. This architecture redefines ocean energy infrastructure as self-sufficient, ecology-integrated power hubs.

The system mitigates the economic viability risks by fundamentally overcoming the limitations of low energy density and operational discontinuity through synergistic multi-gradient harvesting, autonomous self-powered operation, and deep-sea stability. Furthermore, it directly reduces operational costs by eliminating external energy needs, enhancing component durability (PCM, membranes), improving efficiency (cascades, energy recovery), and leveraging intelligent management and cost-effective solutions for key challenges like fouling. These integrated approaches collectively enhance the system's techno-economic viability.

CONCLUSION

This study integrates thermal, mechanical, and electrochemical processes into a unified framework, enabling the transformation of oceanic gradients into a continuous energy cascade. By leveraging thermal expansion to drive motion, which subsequently generates pressure, amplifies salinity, and ultimately powers electrochemical reactions, the proposed system achieves a remarkable enhancement of natural salinity gradients from minimal ΔS to significantly amplified values through selective separation under high-pressure driving forces. This mechanism significantly improves the efficiency of salinity gradient energy conversion technologies such as RED and pressure-retarded osmosis. The core innovation lies in the direct utilization of deep-sea hydrostatic pressure, eliminating the need for external energy inputs. The value of this integrated system lies in its potential to provide sustainable and autonomous power for offshore and underwater applications, such as supporting oceanic monitoring networks, autonomous subsea vehicles, and remote island electrification. By combining energy harvesting with storage in a modular and scalable architecture, this approach offers a resilient solution for continuous ocean-based operations without relying on land-based infrastructure.

Future work will focus on several key directions: advancing material science for more robust pressure-resistant membranes and anti-fouling coatings, optimizing system-level cascade configurations and energy recovery modules, and integrating AI-driven strategies for real-time salinity and fouling management. Further techno-economic analyses and large-scale ocean trials will also be essential to validate the practical feasibility and economic viability of the system in real-world marine environments.

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DECLARATION OF INTERESTS

The authors declare no competing interests.