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Bidirectional Tidal Energy Conversion Using a Countermass and Buoyancy-Coupled Hydraulic System for Low-Range Tide Environments

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Abstract
This paper presents the conceptual design and technical assessment of a novel tidal energy conversion system engineered to operate efficiently in regions with minimal tidal range (~1 meter), where conventional tidal technologies are economically unviable. The proposed system transforms small vertical tidal oscillations into continuous electrical power using a vertically reciprocating architecture centered around two primary components: a Tidal Lift Caisson (TLC) and a Countermass Gravity Block (CGB). The system operates through bidirectional hydraulic action. As the TLC rises with the tide, it pulls the CGB upward, activating the Tidal Uplift Cylinder Assembly (TUCA) to pressurize a high-pressure hydraulic line. Conversely, during tidal recession, the gravitational descent of the CGB engages the Gravity Descent Cylinder Assembly (GDCA), maintaining energy extraction during the downward stroke. Both strokes feed pressurized fluid to a Hydraulic Drive Motor (HDM), which in turn drives a Grid-Sync Generator (GSG) at 1500 RPM. An integrated High-Pressure Buffer Accumulator (HPBA) bridges pressure gaps between strokes to ensure uninterrupted generation. A 1 kW system configuration, - is fully analysed, including energy balance, component sizing, and technology readiness. The caisson (37.7 m diameter) provides buoyancy for both hydraulic work and CGB lifting, while the CGB (2,862.4 tons) supplies gravitational force. All components are selected or scaled for realistic deployment using existing marine and hydraulic technologies. This system addresses the global need for decentralized, low-impact, open-sea tidal energy generation in areas previously excluded from tidal infrastructure investment. It offers modular scalability, mechanical simplicity, and site independence, providing a new pathway for utilizing tidal motion as a continuous, grid-compatible energy source.

1. Introduction

Conventional tidal energy technologies, such as barrage systems or horizontal-axis turbines rely on large tidal head differentials or strong unidirectional currents, limiting deployment to a small number of optimal global locations. This research explores an alternative tidal energy conversion method suitable for open-sea sites with minimal tidal height variation. The system utilizes gravitational and buoyant forces to drive a bidirectional hydraulic generator in response to cyclic vertical sea-level changes.

The novelty lies in the mechanical layout, which includes a vertically guided Countermass Gravity Block (CGB), lifted by a buoyant Tidal Lift Caisson (TLC), and coupled to dual piston-cylinder assemblies that pressurize a closed hydraulic circuit. Power is extracted via a hydraulic motor connected to a grid-synchronous generator. This paper presents the theoretical framework, design calculations, and component-level layout for a 1 kW pilot-scale system, including a full mechanical and hydraulic balance.

2. System layout and operation

The system consists of the following major components.

Seabed Anchoring Assembly:

- Fixed structural base that provides vertical guidance and load support
- Integrated guide rails prevent lateral displacement of the moving assembly

Tidal Uplift Cylinder Assembly (TUCA) / Gravity Descent Cylinder Assembly (GDCA):

- 2 oppositely oriented hydraulic cylinder-piston assemblies mounted atop the Seabed Anchoring Assembly
- Pistons are mechanically linked to the floating component — the Tidal Lift Caisson (TLC)

- The linkage configuration ensures that the TUCA and GDCA operate in **opposite hydraulic cycles** (suction/discharge) during each tidal stroke, upward or downward
- These cylinders are respectively engaged during the upward motion (tidal lift) and downward motion (gravity descent)
- Engaged during upward motion (tidal lift) and downward motion (gravity stroke)
- Both assemblies drive hydraulic fluid into a high-pressure line for energy conversion

Tidal Lift Caisson (TLC):

- Link attached to the top cylinder-piston assemblies (TUCA/GDCA)
- Provides buoyancy lift during rising tide, - acts as vertical puller

Countermass Gravity Block (CGB):

- Reinforced concrete block acting as the primary gravitational energy source
- Located on the top of TLC

Hydraulic Lines:

- High-pressure lines run from both cylinders to accumulator bank and hydraulic motor input
- Return lines connected from motor back to piston reservoirs (closed loop)

Hydraulics and Generator:

- Required subsea enclosure and need to be subsea rated
- High-Pressure Buffer Accumulator (HPBA), - a 50-liter accumulator to maintain pressure continuity. The accumulator temporarily stores high-pressure fluid and releases it at a controlled rate to support continuous operation of the hydraulic drive motor[1].
- Hydraulic Circuit included flow control, return lines, and fluid reservoir
- Hydraulic Drive Motor (HDM), - a hydraulic motor for converting fluid pressure into shaft rotation. Standard hydraulic motors can maintain smooth output at low input flows [3].
- Grid-Sync Generator (GSG), - a standard 1500 RPM generator producing 50 Hz AC power

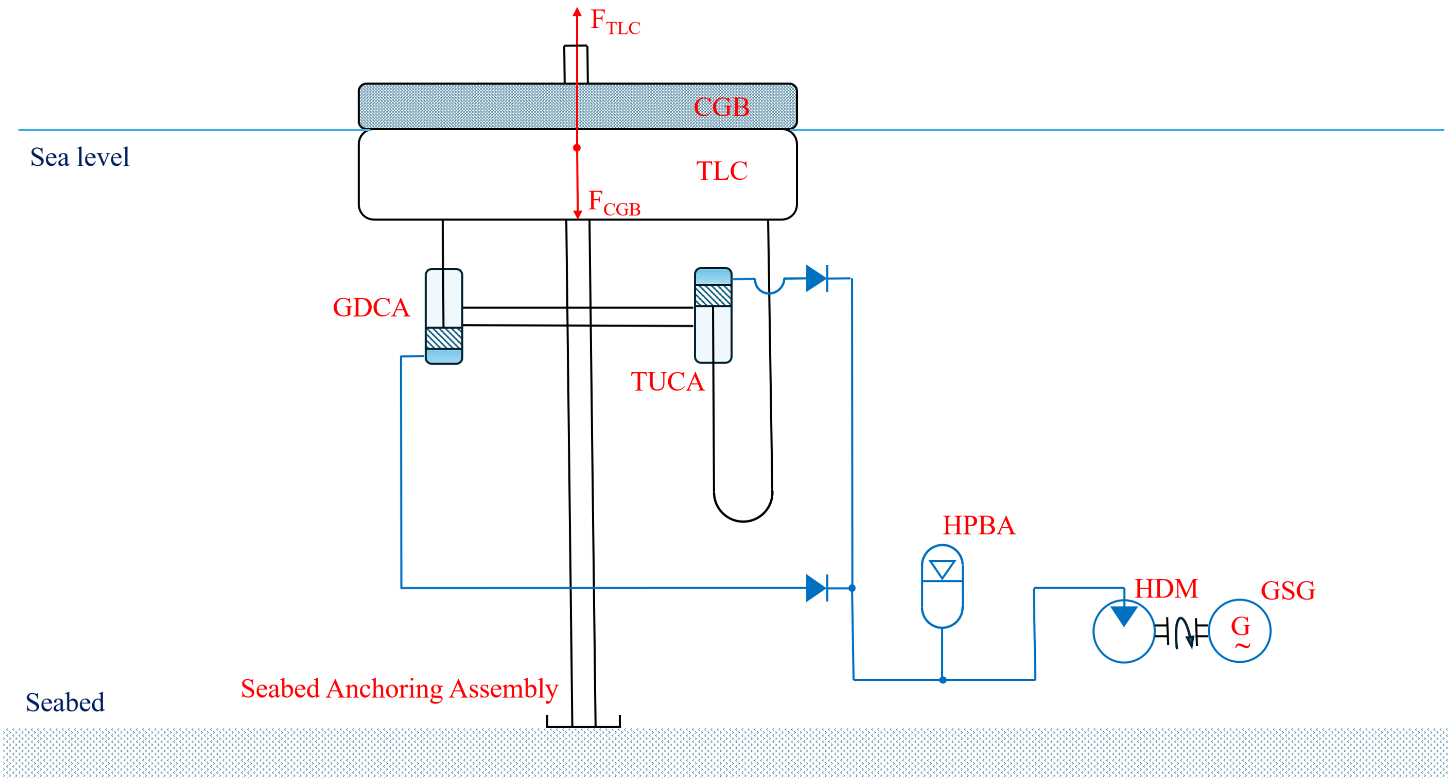

Fig. 1: Schematic diagram of the system.

The upward stroke (TLC rise) engages TUCA, while the downward stroke (CGB fall) engages GDCA. Each piston stroke is designed to deliver sufficient pressure to maintain the generator shaft at required torque and speed, accounting for system losses. All forces, fluid volumes, and energy flows are calculated for a 6-hour tidal stroke.

3. Design Calculations

Energy & power

Net electrical output (design target) is 1.0 kW.

Step-by-Step Efficiency Breakdown as per table below

Table 1: Efficiency Breakdown.

Stage	Estimated Efficiency (%)
Mechanical (piston, guidance)	~95%
Hydraulic (pumping, motor)	~85%
Generator (electrical output)	~95%

Total system efficiency:

$$\eta_{total} = 0.95 \times 0.85 \times 0.95 \approx 0.77 \text{ or } 77\%$$

Total mechanical energy required for 1 kW continuous output over a 6-hour stroke is:

$$P_{mech} = 1.0/0.77 \approx 1.3 \text{ kW} = 1.3\times10^3 \text{ W}$$

Time: T = 6 hrs = 21600 s
Energy per 6-hour tidal stroke:

$$E = P_{mech} \times T = 1.3\times10^3 \cdot 21{,}600 = 28.08\times10^6\ J = 28.08\ MJ$$

Required force per 1m stroke

The force required to deliver 28.08 MJ of energy through the piston over 1-meter (h) vertical stroke is:

$$F_{piston} = E/h = 28.08\times10^6/1 = 28.08\times10^6\ N$$

Since the caisson must overcome both the force needed to generate hydraulic pressure (F_{piston}) and the weight of the Countermass Gravity Block (F_{CGB}), which is designed to deliver a similar amount of energy during the descent phase, the total required lifting force becomes:

$$F_{TLC} = F_{piston} + F_{CGB} = 28.08\times10^6\ N + 28.08\times10^6\ N = 56.16\times10^6\ N$$

Here, the gravity block is dimensioned such that its gravitational force equals the force required to pressurize the hydraulic system: $F_{CGB} = F_{piston}$

Piston area at 350 bar (3.5×10⁷ Pa)

Let's set the system pressure as P=350 bar, - this is a standard and realistic operating pressure for high-power industrial and offshore hydraulic systems. Then, the required area of the piston traveling over 1-meter stroke will be:

$$S_{piston} = F_{piston}/P = 28.08\times10^6\ N/3.5\times10^7\ Pa = 0.8023\ m^2$$

Piston diameter:

$$D_{piston} = 2 \times \sqrt{(0.8023/\pi)} = 1.01\ m$$

Hydraulics (flow rate and accumulator sizing)

Volume of the displaced fluid through any of cylinders (TUCA or GDCA) during single stroke:

$$V = S_{piston} \times 1\ m = 1.01\ m^2$$

Flow rate:

$$Q_{flow} = V/T = 1.01/21600 = 4.68\times10^{-5}\ m^3/s$$

Assuming 5% of the transition gap to bridge flow during dead zones ($T_{transition}$ = 1080 s) the volume of accumulator needs to be:

$$V_{acc} = Q_{flow} \times T_{transition} = 4.68\times10^{-5} \times 1080 = 0.05\ m^3 = 50\ L$$

Caisson buoyant volume and dimensions

The caisson must generate 56.16×10⁶ N upward buoyant force during the upward stroke. The buoyant force acting on a submerged object equals the weight of the displaced water (Archimedes' Principle):

$$F_{TLC} = \rho_{water} \times V_{TLC} \times g$$

Where,
ρ_{water} - density of seawater, ~1025 kg/m³;
V_{TLC} - submerged volume in m³ (assuming TLC is fully submerged) and
g - the standard acceleration of gravity, ~9.81 m/s².
Let's find the required volume of the caisson buoyant TLC:

$$V_{TLC} = 56.16\times10^6/(1025 \times 9.81) = 5585\ m^3$$

Let's now estimate the dimensions of TLC assuming option with 5-meter height (H_{TLC}) the cylindrical caisson:

$$V = \pi r^2 H_{TLC},$$

so, the diameter of the TLC:

$$D_{TLC} = 2 \times \sqrt{[5585/(3.14 \times 5)]} = 37.7 \text{ m}$$

Possible dimensions: 37.7 × 5 meters cylinder

Gravity block weight, volume and dimensions

The mass required to generate 28.08×106 N of gravitational force, $F_{grav} = F_{piston}$:

$$m_{CGB} = F_{grav}/g = 28.08\times10^6/9.81 = 2{,}862{,}385 \text{ kg} = 2{,}862.4 \text{ tons}$$

If we use reinforced concrete ρ_{RC}=2,400 kg/m³, then:

$$V_{CGB} = m_{CGB}/\rho_{RC} = 2{,}862{,}385/2{,}400 = 1{,}192.66 \text{ m}^3$$

Let's now estimate the dimensions of CGB assuming it is located on the top of TLC (occupying same area as TLC) to exclude buoyance effect and simplifying the current design calculation. The height (H_{CBG}) of the concrete layer is going to be:

$$H_{CBG} = V_{CGB}/(\pi \times D_{TLC}^2/4) = 1{,}192.66/(3.14 \times 37.7 \times 37.7/4) = 1.07 \text{ m}$$

1.07 m thick reinforced concrete slab, 37.7 m diameter

4. Technology Readiness Assessment

Let's evaluate each subsystem for feasibility using current (2025-level) industrial capabilities and with regards to baseline design parameters as per table below:

Table 2: Design Parameters.

Parameter	Value
Tidal range/Vertical stroke	1 meter
Continuous net electrical output	1kW
TLC dimensions	37.7 m dia × 5 m high
CGB weight	2,862 tons
Hydraulic pressure	350 bar
Total mechanical energy per 6-hour tidal stroke	56.16 MJ

Tidal Lift Caisson (TLC):

- Equivalent in scale to small floating dry docks, pontoons, or offshore caissons.
- Modular steel buoyancy tanks or reinforced concrete caissons of this size are commonplace.

Feasibility: Fully buildable with current civil/marine engineering practices.

Countermass Gravity Block (CGB):

- Volume: ~1,193 m³ — e.g., 37.7 m dia × ~1.07 m thick slab.
- Similar in size to foundation segments for wind turbine monopiles or jacking platforms.
- Can be precast in modular segments and assembled on-site.

Feasibility: Well within construction norms.

TUCA/GDCA assemblies:

- Required force: 28.08 MN each
- Required pressure: 350 bar
- Piston area: 0.803 m^2 / Diameter ~1.01 m

These are very large hydraulic cylinders, but similar to:

- Offshore jacking cylinders
- Ship-lift pistons
- Civil lifting platforms
- Manufacturers like Bosch Rexroth, Parker Hannifin, and Enerpac offer solutions at this scale[2].

Feasibility: Large, but standard for heavy offshore and infrastructure lifting

Hydraulic Drive Motor (HDM):

- Input: 350 bar, ~1.3 kW, Output: 1500 RPM mechanical drive shaft
- Maintaining smooth rotation from very slow, low-volume hydraulic input over 6 hours might be a challenge. This could be mitigated via application of hydraulic accumulator and flow control valves set to maintain constant motor speed
- Standard hydraulic motors (e.g. axial piston, bent axis) support these specs

Feasibility: Technically standard for precision hydraulic systems

Grid-Sync Generator (GSG):

- 1 kW @ 1500 RPM
- Industrial micro-generators widely available (diesel backup gensets, wind turbine alternators)
- Requires subsea-rated, oil-filled, pressure-compensated housing

Feasibility: Available

HPBA (Accumulator):

- Volume needed: ~50 liters at 350 bar
- Commercially available as Bladder-type (Parker, HYDAC) and Piston-type
- Rated for deep-sea oil & gas and hydraulic power units

Feasibility: Available

What Could Be a Challenge:

- Precise control of stroke phasing. Mitigation: use of flow sensors, valve banks, stroke limiters
- Achievable long-term sealing of large cylinders. Mitigation: use offshore-rated hydraulic seals, pressurized housings
- Structural mass transportation (CGB). Mitigation: precast in sections, tow-float to site, assemble at sea. Consider use of single semi submerged caisson partially filled with water both as TLC and CGB. Design considerations may follow existing offshore concrete structure codes such as DNVGL-ST-C502 [9].
- Long-term structural integrity of the large TLC unit (Ø37.8 m × 5 m height). Mitigation: apply internal bracing and corrosion-resistant coatings; perform FEA validation under fatigue, heave, and pressure conditions; consider use of reinforced concrete over steel for cost and mass distribution control

5 System Optimization Strategy

To enhance the overall energy yield and resilience of the proposed tidal system, the integration of additional renewable elements and value-added conversion technologies is recommended.

The most promising optimization approach involves deploying a solar photovoltaic (PV) array on the upper surface of the TLC/CGB block, - the exposed, above-sea-level section of the floating assembly. Given its large surface area and elevated position, the top of the caisson provides a stable and unobstructed platform ideally suited for mounting PV panels. This configuration enables direct sunlight exposure throughout the day, particularly in equatorial and temperate coastal zones, which can significantly boost net energy production.

The PV array may be designed as a semi-rigid or flexible marine-grade panel assembly integrated into the caisson deck structure. Generated DC power can be stored locally in a dedicated battery accumulator located on the seabed. An inverter unit may then be used to feed this energy into the same grid-connected AC infrastructure already served by the hydraulic-electric conversion system. Alternatively, a marine-grade DC generator could be installed instead of GSG unit driven by hydraulic motor to feed battery accumulator jointly with solar panel system and store DC current.

This hybridization strategy offers multiple operational advantages such as:

- It diversifies energy input sources, providing energy during both tidal slack periods and daylight hours;
- It increases overall system capacity factor without enlarging the mechanical footprint; and
- It enables modular scale-up of energy availability (battery installation) at relatively low marginal cost.

The electrical and structural integration of solar units must account for marine environmental constraints such as saltwater corrosion, bird loading, wind gusts, and UV degradation. Use of anti-fouling coatings, frameless panel anchoring, and encapsulated wiring will help ensure operational durability. Coupling this PV array with real-time system control logic also opens the path for intelligent load dispatch, battery balancing, and predictive maintenance.

As a secondary yet highly strategic optimization pathway, the use of direct DC power for hydrogen production may be explored. In coastal locations where grid export is limited or intermittent, the system's low-voltage DC output can be routed to modular electrolysis units (e.g., PEM-type electrolyzers) to produce green hydrogen[4]. This approach effectively transforms the system into a hybrid power and fuel production node, ideal for remote installations, small ports, or offshore research facilities. While the electrolyzer modules will increase capex, they also allow for full-time utilization of available energy - including surplus during low-demand periods. The produced hydrogen can be stored, compressed, or transferred for later use in power generation, marine fuel blending, or industrial applications.

Overall, this dual-mode optimization—solar power integration and selective DC-to-hydrogen conversion—offers a robust and flexible pathway to improve energy yield, asset utilization, and long-term economic value. These additions further position the tidal unit not only as a passive energy harvester, but as a multifunctional ocean energy platform capable of supporting future decentralized energy infrastructure.

6 Conclusion

This paper presents a novel and modular tidal energy concept specifically designed for deployment in low-tide coastal environments where conventional tidal technologies are ineffective.

By focusing on scalable units with relatively small output (starting at ~1 kW), the design demonstrates strong potential for mass deployment in underserved or off-grid regions. Critical engineering challenges, such as stroke synchronization, mechanical-hydraulic efficiency, and structural stability, - are addressed through a technology readiness assessment. The system's feasibility is further reinforced through the use of well-established technologies drawn from offshore oil and gas, floating platform design, and marine hydraulics.

To maximize efficiency, the proposal includes a solar photovoltaic array mounted on the upper surface of the floating caisson, complementing the tidal cycle with diurnal energy capture. These optimization pathways position the system as a compact, flexible, and locally adaptable ocean energy solution with broad relevance to distributed coastal energy systems

7. References

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