Storm-Only Wave Energy: A Hinged-Flap Harvester with One-Way PTO for Extreme Sea States

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Most wave-energy converters (WECs) are designed to chase average seas with complex, continuously active power-take-offs. Yet ocean climates, like wind, are heavy-tailed: a small number of storm days contain a disproportionate share of annual wave power ($\approx 0.49 \cdot Hs^2 \cdot Te$ kW/m in deep water). We propose a complementary, storm-only architecture: a seabed-hinged flap that converts surge during extreme events via a rectifying power-take-off (PTO)—either a sprag/ratchet mechanical train or a hydraulic check-valve + accumulator "diode bridge." The PTO locks on the power stroke and freewheels on reset, with torsional bias for reliable return and flywheel/supercapacitor or hydraulic accumulators to smooth pulses before the generator/inverter. A simple storm gate (deploy at Hs≥3.5–4.0 m; cap at 6.5–7.0 m with hysteresis) limits duty to high-value, high-energy windows, allowing robust sections, modest RPMs, and low maintenance compared with continuously active WECs. We develop mechanics, control, and siting for headlands, gap exits, and 8–15 m depths, specify a bench/tank/sea test program, and frame economics as premium-time kWh that coincide with coastal grid stress. The concept mirrors a storm-tail wind harvester: harvest on the pull, overrun on the reset, but in water. We argue that storm-focused WECs can raise coastal resilience by monetizing the very hours when conventional fleets curtail, forming a new class of simple, survivable, and grid-useful ocean energy assets.

Keywords: wave energy, storm tail, hinged flap, one-way clutch, sprag, hydraulic rectifier, accumulator, flywheel, supercapacitor, surge converter, oscillating surge, Hs Te gating, rectified PTO, extreme seas, coastal resilience.

A collaboration with GPT-5. 40 pages.

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Referneces

1. Motivation and Background

1.1 The heavy-tailed ocean: annual energy vs. storm days

Ocean wave climates are statistically right-skewed: a small number of storm days contribute a disproportionately large share of the annual wave power flux. In deep water, the long-term, per-meter-crest power is well-approximated by

P_{wave} [kW/m] $\approx 0.49\, H_s^2\, T_e$,

so power grows quadratically with significant wave height H_s and linearly with energy period T_e. Because storm regimes push both H_s and T_e upward, a few events dominate the annual integral. Empirically, many energetic coasts show that the top 5–15% of sea states (ranked by H_s) can carry 30–60% of annual P_{wave}. This "storm tail" mirrors the v^3 leverage in wind: rare, large seas are worth outsized attention. Designing a converter to wake only during that tail lets us trade continuous efficiency for simplicity, survivability, and premium-time energy.

1.2 Limits of continuous WEC operation in extreme seas

Conventional WECs (point absorbers, attenuators, oscillating surge/OWC) are typically optimized to operate continuously across common sea states and to survive extremes, often by de-tuning, latching off, or shedding load when hydrodynamic forces exceed safe envelopes. Practical constraints include:

- Load envelopes & fatigue: Extreme H_s/T_p excite high hinge/bearing loads, slamming, and mooring tensions; PTOs face over-torque and thermal limits.
- Control limits: Reactive control and phase-optimization that boost capture in moderate seas become unstable or unsafe in violent seas; controllers revert to conservative modes.
- Availability vs. protection: To avoid damage, many systems park or bypass PTO in the largest events—precisely when the resource is richest—producing zero or near-zero output during storms.
- Complexity penalty: Continuous-duty architectures require precision hydraulics, valves, or active air turbines and robust grid interfaces year-round, increasing CAPEX/OPEX and the number of failure modes exposed to salt, sand, and biofouling.

Implication: A storm-only, rectified harvester that is mechanically simple, overbuilt, and duty-limited to high-value hours can complement continuous WECs by monetizing energy that they prudently forgo.

1.3 Rectification as a unifying idea (mechanical/hydraulic "diodes")

Wave excitation is oscillatory; grids and generators prefer unidirectional torque and smoother power. The unifying trick is rectification—turning back-and-forth motion into one-way shaft work—plus buffering. Three canonical realizations:

1. Mechanical motion rectifier (MMR):
   A sprag/freewheel/ratchet engages on the power stroke and overruns on reset. Add a torsion spring (return bias) and viscous/eddy damping to shape engagement jerk, then a flywheel on the generator side to smooth pulses.
   - Pros: minimal fluids, simple kinematics, low parts count.
   - Use when: near-shore prototypes, small-to-medium ratings, tight maintenance access.
2. Hydraulic full-wave rectifier:
   A cylinder at the hinge pumps through check valves into a high-pressure manifold/accumulator only during the power stroke; the return stroke bypasses via a low-pressure path. A hydraulic motor then draws one-way flow to spin the generator at near-constant RPM.
   - Pros: inherent energy buffering (accumulators), robust underwater layout, decoupled generator speed.
   - Use when: harsher sites, higher forces, desire to keep electrics topside.
3. Pneumatic rectification (OWC/bi-radial):
   If using an air chamber, select a bi-directional turbine (e.g., Wells/bi-radial) that always spins the same direction for in/out breathing—an aero diode.
   - Pros: no underwater hydraulics or moving seals at the hinge.
   - Use when: chamber geometries are practical; desire minimal wetted mechanisms.

Across all three, add storm gating (deploy at H_s above a threshold; cap above a higher one with hysteresis) so the device works only when the tail is rich and otherwise parks in a low-drag, low-wear state. Rectification + gating yields the same philosophy as our storm-tail wind harvester: harvest on the pull, overrun on the reset, buffer locally, deliver grid-friendly power, and avoid complexity where the ocean will punish it most.

2. Concept and Operating Principle

2.1 Seabed-hinged flap in surge: geometry, stroke, loads

- Geometry. A vertical plate (flap) of width W and height H is pinned to a seabed hinge. Typical pilot scale: W = 2–3 m, H = 3–5 m, thickness selected by local buckling and slam loads. Hinge centerline sits ~0.2–0.4 H above seabed to reduce burial and scour.
- Kinematics. The flap rotates through a bounded sector: theta in [−theta_min, +theta_max], with theta_max ~ 20–30 deg. Under wave forcing, near-bed orbital velocity u_b(t) drives a horizontal surge that produces a moment about the hinge.
- Hydrodynamic loading (lumped form).
    - Horizontal force: F_h(t) ≈ (1/2) rho C_D A_p u_b(t)|u_b(t)| + m_a du_b/dt, where A_p = H * t_effective is projected area (or use panelized sum), C_D is drag coefficient, and m_a is added mass projected onto the flap normal.
    - Hinge moment: M_h(t) ≈ F_h(t) * z_cp, with z_cp the vertical lever (center of pressure to hinge). For small theta, linearize M_h ~ K_hyd * theta + C_hyd * dot(theta) + M_exc(t) (radiation + excitation split).
- Structural checks. Verify: (i) hinge pin bearing pressure and shear; (ii) flap panel bending (slam coefficient margin); (iii) weld toes and cutouts with generous radii; (iv) foundations for combined uplift + moment in design sea states (Hs_cap, Te_cap).
- End stops. Cam-shaped, polymer-faced stops at +/- theta_limit spread impact over a few degrees to curb jerk.

2.2 One-way PTO: sprag/ratchet drivetrain vs. hydraulic check-valve bridge

- Common idea: motion rectification. Convert oscillatory hinge motion into one-direction generator torque; avoid back-driving on the reset stroke.

A) Mechanical train (sprag/ratchet)

- Shaft path: hinge -> torque arm -> one-way device (sprag or roller clutch) -> elastomer coupling -> step-up (belt/gear, G ~ 10–20) -> PM generator -> 3-phase rectifier -> DC bus.
- Harvest stroke: if M_h − M_return − M_damp > M_losses, the sprag locks; power flows to generator.
- Reset stroke: inequality reverses; sprag overruns; generator freewheels; flap returns with minimal load.

- Protections: series torque limiter set at ~1.3x max continuous torque at Hs_cap; deadband window (2–5 deg) around lock/unlock; elastomeric bumpers at stops.

B) Hydraulic bridge (check-valve rectifier)

- Cylinder(s) at the hinge drive a high-pressure (HP) manifold via check valves on the harvest stroke; bypass or low-pressure (LP) return on reset.
- HP accumulators buffer flow; an HP -> hydraulic motor -> PM generator chain delivers smoothed, one-direction shaft power.
- Pros vs. mechanical: inherent pulse smoothing, better sealing in salt/spray, decoupled generator RPM; Cons: fluid components, accumulator maintenance.

Selection guidance. Use mechanical for small/medium pilots with easy access; use hydraulic where forces are high or you want topside generator enclosures and robust submersible PTOs.

2.3 Return bias, damping, and pulse smoothing (flywheel, supercaps, accumulators)

- Return bias. Provide a modest restoring moment so the flap reliably resets without back-driving the generator:
  - Torsion spring at hinge: M_return = k_t * theta (choose k_t so M_return ~ 5–10% of typical harvest moment at deploy sea state).
  - Gravity bias (eccentric counterweight) if space allows.
- Damping / jerk control.
  - Viscous rotary damper or eddy-current brake in series: M_damp = c_t * dot(theta), tuned so engagement rise 10–100 ms; avoids sprag tooth shock and bearing skid.
  - For hydraulics, throttling orifice on the return path gives passive damping.
- Smoothing to grid.
  - Flywheel (mechanical): add inertia J_f on generator shaft to reduce delta_omega during pulses; size so a 0.2 s 2x-rated torque pulse yields < 15% RPM sag.
  - Supercapacitors (electrical): seconds-scale buffer on the DC bus; target E_cap ~ P_avg * 5–15 s with 20–40% SOC swing.
  - Accumulators (hydraulic): the fluid-power analogue; set pre-charge and volume for desired ripple attenuation and motor RPM constancy.

Tuning sequence. (1) pick k_t for reliable reset; (2) add c_t to cap engagement jerk; (3) add J_f and/or caps/accumulators to meet ramp-rate and DC-bus ripple specifications.

2.4 Storm gating: deploy, cap, hysteresis; fail-safe park

- Why gate? Like the wind tail, few storm days dominate annual wave energy. We operate only when seas are rich enough to justify loads and wear.
- Signals. Hs (significant wave height) and Te (energy period) from local buoy or onboard pressure/ADCP; internal signals: theta, dot(theta), M_h, PTO temperature, limiter slip events.
- Thresholds (pilot starting points).
    - Deploy ON: Hs >= Hs_deploy (3.5–4.0 m) AND Te >= Te_min (7–9 s).
    - Cap/reef: Hs >= Hs_cap (6.5–7.0 m) OR M_h >= M_trip (torque trip) OR PTO temp over limit.
    - Deploy OFF: Hs <= Hs_deploy − 0.5–1.0 m (hysteresis).
    - In icing/debris alerts: raise thresholds or force park.
- State logic (simplified).
    - PARKED -> HARVEST when thresholds met; engage sprag/hydraulics, open trims.
    - HARVEST -> CAPPED when cap trip; activate depower (edge-trim, partial reef, or hydraulic bypass).
    - CAPPED -> HARVEST when Hs falls below Hs_cap − hysteresis and Te OK.
    - Any state -> PARKED on faults or wildlife windows.
- Fail-safe park. Springs and cams bias the flap to edge-on, low-drag if power/control is lost; hydraulic bypass valves default open; electrical crowbar/dump prevents DC over-voltage.
- KPIs for gating quality. Event latency < 30 s; false deploys < 1 per event; cap actuation < 0.5 s after threshold; no limiter trips within design sea states.

Summary. A seabed-hinged flap harvests surge in a bounded stroke. A one-way PTO rectifies oscillation to one-direction torque; return bias + damping ensure clean lock/reset; flywheel/supercaps/accumulators deliver inverter-friendly power. With storm gating and fail-safe park, the device works when oceans are most energetic and rests the rest of the year—trading continuous complexity for simple, robust, tail-focused production.

3. Mechanics and Control

3.1 Torque paths, stops, deadbands, and limiter settings

Torque path (lumped):

$$M_{\text{hinge}}(t) = M_{\text{exc}}(t) - M_{\text{rad}}(\theta, \dot{\theta}) - M_{\text{return}}(\theta) - M_{\text{damp}}(\dot{\theta})$$

PTO-side torque when the one-way device is engaged:

$$M_{\text{PTO}} = \eta_m \, \eta_g \, \frac{M_{\text{hinge}}}{G} \text{ (lock)}; M_{\text{PTO}} = 0 \text{ (overrun)}$$

with gear/belt ratio G, mechanical/electrical efficiencies η_m, η_g.

Stops & stroke shaping.

- Limit stroke to $\theta \in [\theta_{\min}, \theta_{\max}]$ (e.g., $\pm 25°$).
- Use cam-faced polymer bumpers that spread contact over ~2–4° to cap jerk and noise.
- Place hinge radial and thrust bearings so stop reactions bypass the sprag housing (avoids brinelling).

Deadbands (to avoid chatter):

- Engagement deadband $\Delta\theta_e$ just before the power arc: the sprag can only lock after $\theta = \theta_e$(typ. 2–5°).
- Overrun deadband $\Delta\theta_r$ near reset: guarantee full disengagement before the stop (2–5°).
- Torque deadband ΔM: controller ignores $| M_{\text{hinge}} | < \Delta M$ perturbations (micro-sea slosh).

Limiter settings (series, upstream of step-up):

- Slip torque M_{slip}: set at $1.2 - 1.4 \times$the worst expected continuous hinge torque at $H_{s,\text{cap}}$.
- Trip torque M_{trip}: a hard mechanical cam that forces depower/edge-trim at $1.6 \times$continuous; this protects against rare slams.
- Verify that $M_{\text{slip}} < \frac{M_{\text{sprag,static}}}{1.5}$ (margin to sprag ultimate).

3.2 Compliance tuning: k_t, c_t, and shared inertia J_f

Purpose: spread engagement impulses over 10–100 ms, avoid tooth/skid events, and shape generator ramp rates.

- Return spring (torsion) k_t:
  $M_{\text{return}} = k_t\, \theta$. Choose k_t so M_{return} at mid-stroke is 5–10% of median harvest torque at deploy sea state; ensures reset without stealing much work.
  Natural torsional period (device side):

$$\tau_n = 2\pi \sqrt{\frac{J_{\text{eq}}}{k_t}} \Rightarrow \tau_n \approx 10 - 30 \text{ ms (target)}$$

- Damping c_t (viscous or eddy):
  $M_{\text{damp}} = c_t\, \dot{\theta}$. Tune time constant $\tau_d = \frac{J_{\text{eq}}}{c_t}$ to 20–80 ms, limiting engagement jerk | $\mathrm{d}\dot{\theta}/\mathrm{d}t$ |and sprag shock ΔM_{eng}.
- Shared inertia J_f (generator/flywheel side):
  Limits $\Delta\omega$from torque pulses:

$$\Delta\omega_g \approx \frac{\int (M_g - M_e)\, dt}{J_{\text{gen}} + J_f}$$

Size J_f so a 0.2 s, 2× rated torque step yields <15% speed deviation at the generator.

- Tuning sequence:
  1. Set k_t for reliable resets in lull bins;
  2. Increase $c_t$to bring ΔM_{eng} below 60% of limiter;
  3. Add $J_f$until DC-bus ripple and inverter ramp-rate meet spec (e.g., ≤10%/s at POI).

3.3 Protection stack: torque limiter, peak capping, auto-edge trim

- Limiter (primary fuse): friction or magnetic hysteresis element in series; slips above M_{slip}. Include temperature derating (−10% per +25 K).
- Peak capping (aero/hydro side):

- Hydraulic PTO: accumulator pre-charge and orifice govern peak flow; bypass valve opens at p_{cap}.
- Mechanical PTO: reef/vent (if flap has trailing vents) or a reset-favoring cam that biases to edge-on at large $|\dot{\theta}|$ or high M_{hinge}.

- Auto-edge trim (fail-safe): spring-biased cam or fin that rotates the flap towards edge-on when control power is lost or when M_{hinge} exceeds M_{trip}.
- Electrical crowbar/dump: DC bus dump resistor engaged if $V_{\text{dc}} > V_{\text{hi}}$ during cap events; protects rectifier/inverter.
- Health monitors: bearing temperature, engagement shock (peak ΔM_{eng}), limiter slip duty (% time), vibration bands; any threshold breach forces PARK.

3.4 Controls: H_s/T_e thresholds, event detection, latching options

Signals: H_s, T_e (from buoy or onboard pressure/ADCP), $\theta, \dot{\theta}$, M_{hinge}, T_{PTO}, V_{dc}, I_{dc}, temps, limiter state.

State machine (storm-gated):

```
if FAULT or wildlife_window or debris_alert: PARK


if state==PARK:
  if Hs>=Hs_deploy and Te>=Te_min and TI<=TI_max:
    ARM(); state=HARVEST


if state==HARVEST:
  if Hs>=Hs_cap or M_hinge>=M_trip or T_PTO>=T_max:
    CAP(); state=CAPPED
  elif Hs <= Hs_deploy - Hs_hyst:
    PARK(); state=PARK


if state==CAPPED:
```

```
if Hs <= Hs_cap - Hs_hyst and Hs >= Hs_deploy:
  UNCAP(); state=HARVEST
elif Hs <= Hs_deploy - Hs_hyst:
  PARK(); state=PARK
```

Recommended starts: $H_{s,\text{deploy}} = 3.5 - 4.0$ m, $T_{e,\min} = 7 - 9$ s, $H_{s,\text{cap}} = 6.5 - 7.0$ m, $H_{s,\text{hyst}} = 0.5 - 1.0$ m.

Event detection & KPIs (per deploy window):

- Reset reliability $\geq 98\%$ (strokes reaching $\theta_{\min}$with overrun).
- Harvest duty $\geq 60\%$ (fraction of time in lock with positive DC power).
- Engagement shock: $P95\ (\Delta M_{\text{eng}}) \leq 0.6\ M_{\text{slip}}$.
- Power quality: DC ripple ≤ 25% (no flywheel) or ≤ 15% (with flywheel/supercaps).

Optional latching for single-cycle gain (advanced):

- Idea: briefly hold the flap near peak hydrodynamic torque, then release to maximize work on one stroke (classical WEC "latching").
- Guardrails: enable only when $H_s$in mid-storm band (e.g., $H_{s,\text{deploy}} + 0.5 \leq H_s \leq H_{s,\text{cap}} - 0.5$); disallow if $|\ \dot{\theta}\ |$or M_{hinge}near limits.
- Timing: phase release at predicted crest-to-trough zero-upcrossing using $T_e$and recent zero-crossings; enforce minimum latch time and maximum duty.

Adaptive thresholds (seasonal learning):

- Fit rolling Weibull/EVT on H_s peaks and update $H_{s,\text{deploy}}$, $H_{s,\text{cap}}$ to maximize kWh/event under constraints on shock rate, thermal headroom, and limiter duty.

Bottom line: Engineer a clean torque window (stops, deadbands), add a compliance chain (k_t, c_t, J_f) to tame pulses, stack protections (limiter, capping, edge-trim, dump), and run a storm-aware state machine (with optional latching) that harvests when the sea's tail is richest and parks when it isn't.

4. Site Selection and Microclimates

4.1 Headlands, gap-exit coasts, 8–15 m depth windows

Geometric accelerators. Favor coastal geometries that focus storm swell and surge without creating chaotic breakers right on top of the device:

- Headlands & capes: Long upwave fetch and refraction concentrate wave energy; set units around the nose but back from plunging-break zones.
  - *Placement:* shoreline offset where breaker index $\gamma_b = \frac{H_b}{h}$ stays below ~0.6 in design storms; target 8–15 m water depth to stay subcritical during most events.
- Gap-exit coasts & straits: Bathymetric "nozzles" (shoals flanked by deeper channels) and island gaps steer and amplify orbital velocities near the bed.
  - *Placement:* leeward shoulder of the gap's core flow where currents are strong but less rotational; avoid zones of rip-induced cross-flow.
- Gently sloping fore-shores (1:50–1:100): Preserve non-breaking storm waves to the device, so surge is coherent and flap strokes are clean.

Bathymetry & substrate.

- Depth: 8–15 m balances storm exposure with constructability; keeps hinge below turbulent breaker layer while still feeling strong surge.
- Seabed: competent rock (preferred) or dense sand with micro-piles; avoid mobile dunes and thick soft muds (scour, settlement).
- Scour & run-up: design skirts or aprons where scour depth exceeds 0.3 h under design seas; avoid reflected clapotis zones.

Access & survivability.

- Tug/ROV reach: choose sites within small-vessel range for maintenance windows.
- Marine hazards: map kelp lines, debris drift, and navigation lanes; keep visual profile low and add cardinal marks where required.

4.2 Tail-first metrics: storm climatology of H_s, T_e, peak periods

We are "tail hunters"—evaluate the high-energy end of the distribution, not the annual mean.

Data to collect (minimum 1–3 storm seasons):

- Bulk sea state: H_s (significant height), T_e (energy period), and peak period T_p at 30–60 min records, plus 1–3 s burst stats during storms.
- Directional spectra (if available): spread function $D(\theta)$ to quantify coherence; narrow spreads (≤ 25–35°) improve flap regularity.
- Near-bed orbital velocity proxy: from ADCP or pressure-derived estimates at z ≈ 0.2–0.4 H (device hinge elevation band).

Tail metrics (deep water approximation unless corrected):

- Wave power flux: $P_{\text{wave}}\ [\text{kW/m}] \approx 0.49\ H_s^2 T_e$.
- Tail share f_{tail}: fraction of annual power from storm band:

$$f_{\text{tail}} = \frac{\sum P_{\text{wave}}\ 1(H_s \geq H_{s,\text{deploy}})}{\sum P_{\text{wave}}}$$

Good: $f_{\text{tail}} \geq 0.35$; *excellent*: $0.45\ -\ 0.60$.

- Hours ≥ deploy: $H_{\geq H_{s,\text{deploy}}}$— target ≥ 150–300 h/yr.
- Inter-event spacing: median gap between storm windows; drives maintenance and state-machine hysteresis.
- Rise time & dwell: time from H_s threshold to plateau (minutes–hours) and sustained duration; shapes PTO thermal design.
- Directional stability: tail-hours vector spread σ $_\theta$ ≤ 30° preferred.

Shallow/depth corrections (when $kh$is small):

- Convert deep-water power to local conditions with group velocity $C_g(kh)$; estimate near-bed orbital velocity amplitude:

$$u_b \approx \frac{\pi H}{T}\ \frac{\cosh\,(k(z+h))}{\sinh\,(kh)}\ |_{z\approx -\,0.6h}$$

Use this to bound hinge moments and confirm that storm waves do not routinely break at device depth.

Pass/fail gates for "optimal" micro-site:

- $H_{\geq H_{s,\text{deploy}}} \geq 200\ \text{h}$ /yrand $f_{\text{tail}} \geq 0.40$
- Tail-hour σ_{θ} ≤ 30°; no persistent breakers in 8–15 m during $H_{s,\text{cap}}$ events
- Maintain navigation and environmental buffers (wildlife corridors, kelp, reefs)

4.3 Array spacing and hydrodynamic interference considerations

Goals: keep each flap in clean surge, avoid destructive hydrodynamic coupling, and preserve maintainability.

First-order spacing (plan view):

- Lateral spacing: $\geq 3\ W$ (center-to-center) to minimize shadowing of horizontal orbital velocities.
- Streamwise spacing: $\geq 2\ H$ to avoid near-field flow distortions and vorticity shed from upstream units.
- Staggered rows: offset by 0.5 pitch laterally to break coherent interference patterns.

Coupling regimes & what to watch:

- Morison-type (small bodies, kh large): Drag-dominated loads; interference mainly via velocity deficit and turbulence—use conservative lateral spacing (≥ 3–4 W).
- Diffraction/radiation (larger W relative to wavelength): Arrays can reflect/diffract; check with BEM or mild-slope models for amplification "hot spots" and dips.
- Standing-wave traps: Avoid alignments that form semi-enclosed pockets with high clapotis; add porosity/vents in frames or re-angle rows by 10–15°.

Foundation & cable layout:

- Leave service aisles (≥ 1.5× flap height) for RIB/ROV access.
- Route wet-mates down-sea to reduce entanglement risk; bundle cables in armored umbilicals with sacrificial saddles at touchdown.

Shared inertia/energy bus (optional for arrays):

- Mechanical: single flywheel on a common generator shaft fed by multiple sprag trains (each with its own limiter).

- Hydraulic: multi-flap HP manifold + accumulators; isolate each flap with check valves; set anti-surge orifices to stop pressure shocks when units engage simultaneously.

Array KPIs (during deploy windows):

- Harvest duty (fleet): ≥ 80% with counterphase staggering.
- Ripple at DC bus: ≤ 15% RMS/avg with shared buffer.
- Cross-coupled trips: < 1 per storm event (ensure limiters and caps don't cascade).
- Per-unit derate from interference: < 10% vs. isolated pilot in same sea state.

Environmental corridors:

- Maintain wildlife and navigation lanes between strings; avoid surf zones favored by marine mammals; use low-profile beacons and AIS where required.

Bottom line: choose geometries that focus storm energy without surf chaos; score sites by tail metrics (hours ≥ deploy, f_{tail}, directional stability); and lay out arrays with generous, staggered spacing and a shared buffer (mechanical or hydraulic) so multiple flaps harvest smoothly without starving each other—or the grid interface.

5. Power and Energy Modeling

5.1 From Hs/Te to wave power: deep/shallow corrections

Deep water (kh >> 1). A standard bulk estimate for wave power per meter of crest:

P_wave [kW/m] ≈ 0.49 * Hs^2 * Te

where Hs = significant wave height [m], Te = energy period [s]. This folds in g and deep-water group velocity.

Finite depth (kh ~ O(1)). Correct with the depth-dependent group velocity Cg(kh):

P_wave = (ρ g^2 / (64π)) * Hs^2 * Tz * n(kh)   [W/m]

n(kh) = 1/2 * (1 + 2kh / sinh (2kh))   (group velocity factor)

Use any consistent period (Te or Tz) with an appropriate spectral relationship. Compute k from the dispersion relation:

ω^2 = g k tanh(k h),   ω = 2π / T

Near-bed orbital velocity for hinge loading checks at elevation z (z negative below SWL):

$u_{b,amp} \approx (\pi H / T) * \cosh(k(z + h)) / \sinh(k h)$

Use $u_{b,amp}$ to bound drag and the excitation moment around the hinge.

5.2 Stroke-to-power mapping: flap hydrodynamics, added mass, radiation damping

Model the flap as a single rotational DOF about the hinge:

$$J_{tot} * \ddot{\theta} + C_{rad}(\theta,\dot{\theta}) + K_{hydro}\,\theta + C_{struc}\,\dot{\theta} = M_{exc}(t) - M_{PTO}(t) - M_{return}(\theta)$$

- $J_{tot} = J_{flap} + J_{added}$ (structural + added inertia)
- $C_{rad}(\cdot)$ = radiation damping (hydrodynamic), linearized to $B_{rad}\,\dot{\theta}$ around small strokes
- K_{hydro} = small-angle stiffness from hydrostatics + restoring
- C_{struc} = structural/viscous damping
- $M_{exc}(t)$ = excitation moment from incident waves
- M_{PTO} = PTO reaction moment (load seen at the hinge)
- $M_{return} = k_t * \theta$ (torsion spring)

Linear frequency-domain (for spectral estimates).
With harmonic forcing at ω:

$$(-\omega^2 J_{tot} + j\,\omega\,B_{rad} + K_{hydro} + j\,\omega\,C_{struc} + Z_{PTO})\,\Theta(\omega) = M_{exc}(\omega)$$

where Z_{PTO} is the equivalent (complex) PTO impedance mapped to the hinge:

- Mechanical sprag train (locked): $Z_{PTO} \approx B_{PTO\_mech}$ (damping-like) + $j\,\omega\,J_{ref}$
- Hydraulic check-valve path: $Z_{PTO} \approx B_{PTO\_hyd}(\Delta p,Q) + j\,\omega\,J_{eq}(hyd)$

Excitation moment spectrum.
Use panel or strip theory (Morison/diffraction hybrid) to obtain $|M_{exc}(\omega)|^2$ for a JONSWAP (or measured) spectrum $S(\omega)$. First-order mean absorbed power with a linear PTO damping B_{PTO}:

$$P_{abs} \approx \int (B_{PTO} * \omega^2 |\Theta(\omega)|^2)\, d\omega$$

$$= \int (B_{PTO} |M_{exc}(\omega)|^2) / | -\omega^2 J_{tot} + j\,\omega\,(B_{rad} + C_{struc} + B_{PTO}) + K_{hydro} |^2\, d\omega$$

This shows the classic trade: more B_{PTO} broadens the capture but lowers peak response; too little B_{PTO} wastes excitation by letting the flap swing without doing work.

Time-domain (rectified strokes). For nonlinear, bounded-stroke operation with stops and deadbands, integrate:

For each time step:

compute $u_b(t) \rightarrow F_h(t) = 0.5\, \rho\, C_D\, A_p\, u_b\, |u_b| + m_a\, du_b/dt$

$M_h(t) = F_h(t) * z_{cp}$

Update θ, $\dot{\theta}$, $\ddot{\theta}$ from rotational EOM including $M_{PTO}(t)$, $k_t\, \theta$, $c_t\, \dot{\theta}$

If (power arc) and (sprag condition met): $M_{PTO} = map\_to\_hinge(\tau_{gen} + \tau_{friction})$

Else: $M_{PTO} = 0$

$P_{gen}(t) = \eta_{elect} * \tau_{gen} * \omega_{gen}$ (ω_{gen} from step-up ratio * $\dot{\theta}$)

Then low-pass $P_{gen}(t)$ through the flywheel/supercap/accumulator model to get inverter-side power.

5.3 Rectified PTO models: mechanical vs. hydraulic efficiency chains

A) Mechanical motion rectifier (sprag + step-up + PMG).
Map hinge torque to generator side with ratio G and efficiency η_{mech}:

$\tau_{gen} = (\eta_{mech} / G) * M_{hinge}$ (lock only); $\tau_{gen} = 0$ (overrun)

$\omega_{gen} = G * \dot{\theta}$

$P_{elec} = \eta_{elec}(\omega_{gen}, I) * \tau_{gen} * \omega_{gen}$

Typical chain:

$\eta_{mech} \approx \eta_{sprag} * \eta_{belt/gear} * \eta_{coupler}$ (0.85–0.92)

$\eta_{elec} \approx \eta_{rect} * \eta_{PM} * \eta_{inverter}$ (0.85–0.95 at design point)

Include engagement losses (impact → heat) via an equivalent impulse loss term or by c_t tuning that limits ΔM_{eng}.

B) Hydraulic check-valve bridge + accumulators + hydromotor + PMG.
Power on harvest stroke only (rectification by check-valves). Cylinder flow and pressure:

$Q = A_{cyl} * v_{cyl}$, p rises into HP manifold ($p \le p_{cap}$)

$P_{hyd,HP} = p * Q$

$P\_mech\_gen = \eta\_mot(p,Q) * P\_hyd,HP$

$P\_elec = \eta\_elec * P\_mech\_gen$

Round-trip hydraulic–electric efficiency at design:

$\eta\_chain \approx \eta\_cyl * \eta\_valves * \eta\_accum * \eta\_mot * \eta\_PM * \eta\_inv$ (0.60–0.80 realistic)

Accumulators smooth Q(t) and p(t); set precharge and volume to achieve the desired ripple at the motor shaft. Map the motor's inertia and damping back to an equivalent hinge impedance for coupling studies.

Choosing the chain.

- Mechanical MMR: higher peak efficiency at small/medium scale; simpler but nearer to splash/salt.
- Hydraulic: lower peak efficiency but superior smoothing, sealing, and topside generator placement for harsher sites.

5.4 Seasonal AEP_d and interannual variance; premium-time valuation

Seasonal energy (AEP_d). Integrate absorbed power over *deploy windows* only. Two practical paths:

(i) Spectral binning (bulk):

1. Build a 2D histogram over (Hs, Te) from buoy or onsite records.
2. For each bin, compute P_abs(Hs,Te) using either the spectral formula (linear PTO) or a calibrated time-domain surrogate.
3. Seasonal AEP_d:

$AEP\_d \approx \Sigma\_bins\ P\_abs(Hs\_i, Te\_j) * hours(Hs\_i, Te\_j; \text{deploy policy})$

Include depth corrections and a duty factor for gating (harvest duty within deploy hours).

(ii) Time-march (preferred with rectification):

1. Use 1–3 s burst records (or synthesize irregular seas with JONSWAP) for all hours flagged as deploy-capable by policy.
2. Simulate θ(t), P_gen(t), smoothing, and clipping (caps/reef).
3. Sum kWh/event → kWh/season.

Interannual variance (IAV).

- Heavy tails imply IAV ≈ 20–40% for storm-band hours and energy. Quantify with block-bootstrap on yearly records or fit an EVT model to annual maxima-over-threshold of Hs and propagate into P_abs.
- Portfolio reduction: deploy across uncorrelated microclimates; IAV scales roughly with sqrt(N) for weakly correlated sites.

Premium-time valuation.
Not all kWh are equal. Let v_t be the marginal value (e.g., real-time LMP or microgrid VOLL proxy) and p_t the delivered power:

$$V_{season} = \Sigma_t \; v_t * p_t * \Delta t$$

Storm-only generation often coincides with:

- Grid stress (line trips, repairs, wind-fleet cut-outs inland, winter peaks).
- Microgrid scarcity (diesel outages, port operations during storms).

Define a value uplift factor:

$$U_{value} = (\Sigma_t \, v_t \, p_t) / ((\Sigma_t \, p_t) * v_{avg})$$

Typical expectation: U_value > 1.0 (e.g., 1.2–1.5) if storms align with high prices or high resilience value. Report both energy AEP_d and value-weighted AEP_d to capture portfolio benefit.

Putting it together (planning worksheet).

- Inputs: depth h, (Hs,Te) time series, device geometry, k_t, c_t, J_f, PTO choice and efficiencies, gating thresholds.
- Outputs: per-event kWh, seasonal AEP_d, DC ripple, ramp-rate compliance, IAV band, and value-weighted benefit.
- Acceptance: AEP_d within ±20% of pilot measurements; ripple ≤ 15% with buffer; IAV mitigated via siting; U_value >= 1.2 for resilience-focused portfolios.

Bottom line. Start with Hs/Te → P_wave (depth-corrected), map to hinge excitation → flap response → PTO, then pass through the rectifier + buffer to the grid. Compute AEP_d on deploy windows, carry IAV with EVT or bootstrap, and present both kWh and value-weighted metrics—because storm hours are not just energy-rich, they are system-critical.

6. Prototype and Test Plan

6.1 Bench rig: 1 m lever, sprag PTO, torsion return, damper, flywheel

Purpose. Validate the rectified cycle (lock on power stroke, overrun on reset), quantify engagement shock, tune compliance (k_t, c_t, J_f), and characterize pulsed power before wet testing.

Rig layout (dry).

- Lever + hinge: 1.0 m aluminum arm on dual deep-groove bearings; optical encoder (≥ 1024 CPR) on hinge.
- Actuation (sea surrogate): programmable torque motor (or gravity cam/weight drop) delivering step-rise moments with 50–200 ms edges and 1–5 s dwell; optionally add a "gust" waveform $M(t) = M_0 + \Delta M \sin^2(\pi t/T)$.
- PTO (mechanical): hinge → torque arm → sprag/roller clutch → elastomeric coupling → step-up (G = 10–20) → PM generator → 3-ϕ rectifier → DC bus.
- Compliance: torsion spring (k_t adjustable) in series; rotary viscous or eddy-current damper (c_t); flywheel on generator shaft (J_f).
- Sensors (time-synced): $\theta, \dot{\theta}$; torque cell (or reaction torque via load cell); V_{dc}, I_{dc}; generator RPM; temperatures (stator, bearings); IMU near sprag housing (jerk).
- Stops & deadbands: cam-faced polymer stops at $\pm 25°$; engagement/overrun deadbands 2–5°.

Test matrix.

- k_t: low/mid/high → set $\tau_n = 2\pi\sqrt{J_{\text{eq}}/k_t} \approx 10 - 30\ \text{ms}$.
- c_t: none/mid/high → $\tau_d = J_{\text{eq}}/c_t \approx 20 - 80\ \text{ms}$.
- J_f: none/0.5/1.0× baseline (target <15% RPM sag for a 0.2 s 2× pulse).
- G: 10/15/20. Sprag vs. bicycle freewheel (A/B for chatter).

Procedures & KPIs.

- Engagement shock: $P95(\Delta M_{\text{eng}}) \leq 0.6\ M_{\text{slip}}$; no tooth skip.
- Reset reliability: ≥ 99% in lull sequences (all strokes reach $\theta_{\min}$ with overrun confirmed).
- Power quality: DC ripple (RMS/avg) ≤ 25% (no flywheel) and ≤ 15% (with flywheel/supercaps).

- Thermal margins: $\Delta T_{stator} \le 60$ K during 20-min pulse trains; rectifier ≤ 90 °C.
- Data products: engagement phase plots (±0.5 s), P(t) envelopes, thermal run-ups, parameter table yielding a recommended tune set $\{k_t, c_t, J_f, G, \Delta\theta_e, \Delta\theta_r, M_{\text{slip}}\}$.

6.2 Wave-tank scaling (JONSWAP), latching tests, trim cams

Scaling framework. Use Froude similarity: keep $Fr = U/\sqrt{gL}$ and H/L consistent. At geometric scale $\lambda = L_m/L_p$:

- Period $T_m = \sqrt{\lambda}\, T_p$; velocity $U_m = \sqrt{\lambda}\, U_p$; force $F_m = \lambda^3 F_p$; moment $M_m = \lambda^4 M_p$.
- If viscous effects emerge at small scale, match Re as best-effort on bearings/dampers; use eddy damper analogs to preserve τ_d.

Tank hardware.

- Scaled flap: width $W_m = \lambda W_p$, height $H_m = \lambda H_p$, hinge at scaled elevation; interchangeable edge-trim cam and vent/reef plates.
- PTO emulators:
  - *Mechanical path:* miniature sprag + step-up + micro-PMG + flywheel.
  - *Hydraulic path:* micro-cylinder + check valves → small accumulator → orifice-loaded motor (electrical dyno).
- Metrology: wave probes, stereo cameras for $\theta(t)$, 6-axis load cell at hinge, pressure sensors for chamber/added-mass studies; DAQ ≥ 200 Hz.

Sea states & spectra.

- Generate JONSWAP spectra with γ=3.3, target bins spanning deploy and cap bands (e.g., prototype H_s =3.5, 5.0, 6.5 m and T_e =7–11 s mapped to model scale). Include directionality if facility allows.

Experiments.

1. Baseline capture: no latching, fixed trim. Measure P_{abs} vs. B_{PTO}; derive equivalent $B_{\text{rad}}, J_{\text{added}}$ by fit.
2. Trim cams: power arc broadside; reset arc edge-on. Quantify reset time ↓ and engagement shock ↓.

3. Latching trials: hold near peak torque then release; sweep latch duration and release phase; enforce safety caps.
4. Array pair: two flaps at 3 W lateral spacing, staggered; check interference, duty, and ripple reduction with counterphase.

Acceptance.

- Scale-consistent hinge moments and stroke PDFs; ≥ 20–30% reset-time reduction with trim cam; +10–20% kWh/event gain with latching (mid-storm bins) without exceeding shock/thermal limits (scaled).
- Deliver calibrated models (time-domain and spectral) to predict prototype P(t).

6.3 Outdoor pilot (8–15 m depth): KPIs—reset ≥ 98%, harvest duty ≥ 60%, P(t) smoothing, thermal margins

Site & structure.

- Depth: 8–15 m; leeward shoulder of headland or gap-exit coast; competent substrate for micro-piles or gravity plinth.
- Prototype geometry: $W = 2 - 3\ \mathrm{m}, H = 3 - 5\ \mathrm{m}, \theta_{\max} \approx \pm 25^{\circ}$.
- PTO choice: start mechanical (sprag + PMG) for instrumentation access; consider hydraulic if debris/spray severe.
- Buffers: generator flywheel sized from 6.1; optional 2–5 s supercap on DC bus.

Instrumentation (time-sync to buoy/ADCP).

- Hinge: $\theta, \dot{\theta}$, torque cell, bearing temps/vibration.
- PTO: clutch engagement channel, limiter slip monitor, PMG RPM, V_{dc}, I_{dc}, stator temps.
- Metocean: pressure sensor for local H_s/T_e, ADCP (if available), debris/icing flags.
- Video for stroke/sea correlation (optional thermal/IR at night).

Storm-gate policy (initial).

- Deploy: $H_s \geq 3.8\ \mathrm{m}\ \&\ T_e \geq 8\ \mathrm{s}$.
- Cap: $H_s \geq 6.8\ \mathrm{m}$ or $M_{\text{hinge}} \geq M_{\text{trip}}$ or PMG T >limit.

- Hysteresis: 0.7 m on H_s. Fail-safe park on any fault/wildlife window.

KPIs (pass/fail).

1. Reset reliability: $\geq 98\%$ of strokes reach $\theta_{\min}$ with confirmed overrun during deploy windows.
2. Harvest duty: $\geq 60\%$ of deploy time in lock with positive DC power (per event).
3. P(t) smoothing: DC-bus ripple ≤ 15% RMS/avg with buffer; inverter ramp-rate ≤ 10%/s; no DC over-voltage events.
4. Thermal margins: ΔT_{stator} ≤ 60 K; rectifier ≤ 90 °C over worst storm hour.
5. Structural/drive health: $P95(\Delta M_{\text{eng}}) \leq 0.6\, M_{\text{slip}}$; zero sprag tooth skips; zero limiter fuse events within design seas.
6. Energy realism: event kWh within ±20% of tank-calibrated model; seasonal AEP $_d$ inline with tail climatology.

Operations & H&S.

- Fail-safe edge-trim on loss of power; manual E-stop to hydraulic bypass or electrical dump.
- Exclusion zone: ≥ 1.5× flap height; navigation marks/AIS as required.
- Service windows: hinge-down or diver/ROV procedures; hot-swap panelized flaps and sprag cartridge.

Data & deliverables.

- Event-by-event plots: $H_s(t), T_e(t), \theta(t), M(t), P(t)$, temps; KPI tables; failure/near-miss log.
- Tuned parameter set for site: $\{k_t, c_t, J_f, H_{s,\text{deploy}}, H_{s,\text{cap}}, M_{\text{slip}}$, trim cam profile$\}$.
- Scale-up memo: projected AEP $_d$/kW and value-weighted uplift, array spacing recommendation, CAPEX/OPEX lessons.

Timeline (indicative).

- Month 0–1: bench rig build + tuning.
- Month 2: tank campaign (7–10 days); calibration.
- Month 3–6: pilot install; 30–90 days storm season logging; mid-campaign retune if KPI short.

- Month 6: report + go/no-go for multi-flap array or hydraulic PTO variant.

Success definition. Meet all KPIs above, demonstrate stable, smoothed power during storms, validate models within ±20%, and record no drivetrain/structural excursions—unlocking multi-unit, counterphase arrays for the selected microclimate.

7. Environmental and Marine Engineering Considerations

7.1 Corrosion, abrasion, biofouling; coatings and seals

Materials & corrosion strategy

- Primary steelwork: S355/S420 with C5-M epoxy–polyurethane system (≥ 320 µm DFT) + hot-dip galvanizing for secondary steel; design corrosion allowance 2–4 mm on splash/atmospheric zones.
- Aluminum flap option: 5xxx/6xxx marine grades with isolation kits (non-conductive bushings/washers) at dissimilar joints.
- Cathodic protection: Al–Zn–In anodes sized for 20-year design (or impressed current if many units share a ground); include test coupons and reference electrodes for annual CP surveys.

Abrasion & impact

- Leading edges / stop faces: replaceable UHMW-PE or polyurea sacrificial skins; bolt-on bumpers at end-stops.
- Sediment & surf spray: splash guards over sprag/gearbox; labyrinth or bellows around rotating seals; drain/weep holes on hollow members.

Seals & bearings

- Submerged bearings: double-lipped nitrile/Viton + water-block grease; consider composite sleeve bearings (Thordon-type) for debris tolerance.
- Hydraulics (if used): stainless tube, 37° flare/JIC or Autoclave fittings; wiper + rod seals; subsea wet-mate connectors on sensors.

Biofouling

- Antifouling: copper-free foul-release silicone on flap faces; hard epoxy tie-coat on frames for high-pressure cleaning.

- Design for cleaning: smooth radii, minimal crevices; panelized flap skins for quick swap; mark lift points and ROV-friendly shackle eyes.

Inspection cadence (typical)

- Quarterly visual (ROV or diver): coating nicks, anode consumption, seal weep, debris.
- Annual NDT: MPI/UT at hinge weld toes, pin/bush wear check, torque-limiter slip test, anode audit (> 50% mass remaining target).
- After storm cap events: rapid check of stops, bumpers, sprag housing fasteners, and dump-load thermal logs.

7.2 Wildlife, debris, and navigation safety; low-profile frames

Wildlife

- Collision risk: low—device operates near-bed at low RPM and only in storms when animals avoid surf. Maintain wildlife corridors between strings (≥ 1.5× flap height).
- Acoustics: hold underwater noise < regional thresholds; favor mechanical MMR with damping over valve chatter; test 1/3-octave spectra during pilot.
- Icing/haul-out: no deck surfaces; use rounded crowns on exposed frames to deter haul-outs; avoid pupping seasons for heavy works.
- Curtailment windows: programmable PARK during sensitive migrations or marine-mammal advisories.

Debris management

- Screens & guards: coarse inlet bars on hinge pockets; tapered fairings on flap edges to shed kelp/lines.
- Breakaway logic: sacrificial shear keys on non-critical fairings; over-torque trips force edge-trim to minimize snag loads.
- Debris sensing: spike in M_{hinge} at low H_s, sustained strain on one quadrant, or vibration signature → ALERT → PARK.

Navigation safety

- Low profile: keep topside hardware below charted clearance; only minimal marker posts where required.

- Aids to navigation: IALA-compliant cardinal marks, night lights, AIS AtoN (virtual or physical), and updated charts/NTMs.
- Setback & clearance: meet port authority offsets; provide service lanes and RIB turning circles within arrays.

Emergency states

- Fail-safe park: loss of power/control → edge-on via spring/cam; hydraulics default bypass open; inverter to dump.
- Manual override: surface umbilical or diver-accessible E-stop to vent accumulators or open sprag bypass.

7.3 Installation, inspection, and modular swaps (panelized flaps)

Foundations & install

- Foundations: micro-piles (drilled/grouted Ø140–220 mm) or gravity plinth with skirt; pre-cast stools with hinge seats and indexing cones for diverless alignment.
- Lifts: pre-rigged spreader bars; quick-release lifting lugs with ROV-cap shackles; install during neap tides and low sea states.
- Cabling: armored dynamic umbilical to seabed clamp; trench/bury shore leads; wet-mate at base for PTO pods and sensors.

Commissioning

- Dry-run hinge stroke; verify sprag lock/overrun windows; functional test of dump resistor, limiter slip at set torque, and fail-safe park.
- Sync metocean (buoy/pressure) with controller; write initial $H_{s,\text{deploy}}$, $H_{s,\text{cap}}$, hysteresis.

Inspection & service playbook

- ROV fast-look (post-storm): camera sweep of stops, flap edges, cable touchdown, anodes.
- Diver/ROV annual: pin pull-test, bush play measurement, coating touch-ups using splash-zone epoxies, anode replacement if < 30% mass.
- Predictive: review engagement-shock and slip-duty stats; pre-emptive swap of sprag cartridge and bumpers when thresholds are approached.

Modular swaps (downtime minimization)

- Panelized flap: skin in 2–4 bolt-on panels (GRP/aluminum); swap from RIB with A-frame; target < 3 h per unit.
- Hinge cartridge: pin + bush assemblies extracted with portable C-frame press; keep spares pre-greased.
- PTO pods: mechanical and hydraulic pods on four-bolt rails with wet-mate harnesses; lift as a unit for workshop repair.
- Standardized parts: same sprag, bumpers, seals across the fleet; kitted storm spares (1 set/5 units).

Documentation & compliance

- Environmental Management Plan (EMP): spill kits, biosecurity (anti-foul transfer), species observation log, seasonal curtailments.
- Workpack: lift plans, torque specs, confined-space/lock-out procedures for accumulators and DC bus, dive RAMS.

Design-for-decommissioning

- Reversible pile caps; grout-free shoes where feasible; recoverable anodes; document as-built to ease permit close-out.

Bottom line: engineer for salt, sand, growth, and rare violence—with robust coatings/CP, debris-tolerant seals, quiet mechanics, and swap-friendly modules. Keep the device low-profile and predictable for wildlife and mariners. Plan installation and service so a small crew with a RIB and a day-boat can install, inspect, and hot-swap components quickly, even at the gnarly sites that make the energy pencil out.

8. Economics and Grid Integration

8.1 CAPEX drivers: hinge/base > PTO > controls; sacrificial panel strategy

- Cost stack (pilot → early fleet, per unit):
    - Hinge & foundation (40–55%): micro-piles or gravity plinth, hinge stool, pin/bush set, install vessel time. Cost is dominated by site class (rock vs. sand) and lift logistics.

- PTO module (25–35%): sprag cartridge + step-up + PMG (or cylinder/valves/accumulators + hydromotor); includes flywheel or accumulator pack.
- Frame & flap (10–20%): panelized flap skins, stops/bumpers, guards, anodes.
- Controls & power (5–10%): sensors, rectifier/inverter, DC bus, dump, shore tie, SCADA.

- Design lever—sacrificial panels: keep structural frame long-life, make flap skins consumable (bolt-on GRP/aluminum with replaceable UHMW edges). Aim for < 10% of unit CAPEX per panel swap at end of wear life.
- Standardization: one hinge cartridge, one sprag size, common rectifier/inverter across SKUs → reduces spares and training.
- Civil minimization: choose sites and geometries that avoid heavy piling and large cranes; use precast stools and day-boat lifts to flatten install costs.

8.2 OPEX in salt/sand; condition-based maintenance from shock metrics

- Baseline OPEX drivers: coatings touch-ups, seal/bearing wear, sprag/belt service, anodes, periodic flap-skin swaps, inspection vessel days.
- CBM (condition-based maintenance) signals:
    - Engagement shock ΔM_{eng}: trend the 95th percentile; a rising slope flags sprag wear or damping drift.
    - Limiter slip duty (% time near M_{slip}): high duty → retune k_t, c_t or lower deploy threshold.
    - Bearing temp & vibration bands: early indicator for lubrication or misalignment.
    - Reset failures (% strokes not reaching $\theta_{\min}$): flags debris, seal drag, or return-spring fatigue.
- Service cadence (target): quarterly ROV visual; annual pin/bush gauge + sprag cartridge check; panel swap every 2–4 storm seasons depending on site abrasion.
- Spares & kitting: pre-greased hinge cartridges, sprag pods, bumper kits, seal packs; storm spares staged locally to compress downtime during season.

- OPEX guardrails: design KPI is < 3–5% of CAPEX per year at "good" sites; CBM aims to halve reactive callouts vs. fixed-interval maintenance.

8.3 DC/AC coupling, ramp-rate control, microgrid roles, storm-capacity adders

- DC coupling (recommended for pilots/arrays):
  - Rectify each unit to a shared DC bus with supercaps (seconds) or accumulators → hydromotor smoothing.
  - Advantages: lossless power sharing among units, simpler MPPT-like dispatch, and single inverter class per array.
  - Integrate dump resistor and crowbar at the bus to cap transient over-voltage during cap/reef events.
- AC coupling (when grid intertie exists):
  - Individual inverters per unit or string; leverage grid codes (LVRT/FRT). Slightly higher balance-of-plant, simpler fault isolation.
- Ramp-rate compliance: tune J_f (flywheel) / accumulator discharge and inverter controls to meet ≤ 10%/s ramp at POI.
  - Practical rule: buffer energy $E_b \geq P_{\text{avg}} \times (5\text{–}15)$ sto hit flicker limits with margin.
- Value stacking / premium-time energy:
  - Storm production often coincides with high LMP or outage risk. Define value uplift
    $U_{\text{value}} = \frac{\sum v_t p_t}{v_{\text{avg}} \sum p_t}$; target 1.2–1.5× in coastal feeders or microgrids.
  - Stack with resilience products: black-start support (DC bus → inverter ride-through), non-spinning reserve during storms, or port microgrid contingency power.
- Microgrid roles (ports, islands, coastal communities):
  - Storm capacity adder: commit kW during storm windows when PV is low and inland wind fleets are curtailed/iced.
  - Fuel displacement: shave diesel peaks during severe weather; even modest kWh/event save high-cost liters.

- Emergency mode: auto-islanding with predefined storm profiles (reduced ramp, conservative caps) and priority loads (pumps, comms).

- Interconnection pragmatics:
    - Co-locate near existing harbor substations or turbine interties; share roads/SCADA; plug into existing permits where feasible.
    - Metering: event-based billing ("storm windows"), or capacity credits for committed kW during named conditions (Hs/Te thresholds).
- Illustrative pro-forma (order-of-magnitude, per 5 kW-avg pilot):
    - CAPEX: ${$180–250k} installed (foundation-heavy site → upper bound).
    - OPEX: ${$6–10k}/yr with CBM and day-boat access.
    - Energy: 35–60 MWh/yr at tail-rich site (duty only in storms).
    - LCOE (energy-only): ${$0.20–0.35}/kWh pilot scale → improves at array scale via civil reuse and shared inverter.
    - Value-weighted: with $U_{\text{value}} = 1.3$ and resilience credits, effective LCOE can fall into ${$0.15–0.25}/kWh equivalents for the host microgrid.
- Scale effects:
    - Arraying 6–12 units around one base frame/inverter spreads civil and interconnect costs; expect 15–30% CAPEX reduction per unit and ~2–4¢/kWh LCOE drop.
    - Hydraulic manifolds with shared accumulators further cut ripple and let a single motor-generator right-size for average storm power.

Takeaway. Treat the device as a storm capacity module more than a baseload generator. Keep civil costs down, OPEX predictable with CBM, smooth the DC bus to meet grid codes, and monetize premium-time kWh when systems are stressed. In that niche, simple rectified mechanics can deliver outsized portfolio value relative to their nameplate.

9. Limitations and Risks

9.1 Lower capture in fair seas; deliberate low duty cycle

What it is. By design, the harvester does not run in common sea states. Annual energy hinges on deploy windows (hours with $H_s \geq H_{s,\text{deploy}}$and $T_e \geq T_{e,\min}$). In average years or mellow climates, AEP $_{d}$ can underwhelm relative to continuously-active WECs.

Implications

- Low annual CF: nameplate capacity factors can be 5–15% (storm-only) vs. 20–35% for optimized, continuous WECs at the same coast.
- Value vs. energy: kWh arrive during premium, stressed hours; energy totals may be modest even when value-weighted benefits are strong.
- Siting sensitivity: AEP $_{d}$ scales roughly with the tail share f_{tail} and the hours ≥ deploy; small errors in tail characterization swing outcomes.

Mitigations

- Tail-first prospecting: require $f_{\text{tail}} \geq 0.35$ and $H_{\geq H_{s,\text{deploy}}} \geq 150$–300 h/yr before capex.
- Policy tuning: adjust $H_{s,\text{deploy}}$ down only if engagement shocks and thermal margins remain within limits; otherwise accept lower duty.
- Stacked roles: co-locate with PV/wind/diesel microgrids to monetize storm capacity and ramp services; contract on availability during named sea states, not just energy.

9.2 Shock/fatigue at hinge and PTO; mitigation via compliance and gating

What it is. Violent, short-rise loads create engagement shocks and high cycle–low amplitude fatigue in the hinge, sprag housing, pins/bushes, and stops. Repeated near-limit events accelerate wear.

Failure modes

- Tooth/brinelling: sprag/roller clutch micro-skid at lock-in → surface pitting.
- Pin/bush ovalization: cumulative plastic strain from asymmetric stop hits.
- Crack initiation: weld toe at hinge stools; notch effects at cutouts.
- Thermal overrun: generator/rectifier heating under pulse trains with insufficient smoothing.

Quantification

- Target engagement rise 10–100 ms; design $P95(\Delta M_{\text{eng}}) \leq 0.6\ M_{\text{slip}}$.
- Miner's rule with rainflow on $M_{\text{hinge}}(t)$; require damage index $D_{\text{year}} \leq 0.15$ at 20-yr life (including safety factors).
- Thermal: $\Delta T_{\text{stator}} \leq 60$ K during worst 20-min pulse trains; rectifier case $< 90°$C.

Mitigations

- Compliance chain: tune $\{k_t, c_t, J_f\}$ to spread impulses; add cam-faced stops and elastomer bumpers.
- Torque fusing: friction or magnetic limiter at $1.2 - 1.4 \times$ worst continuous torque; trip at $1.6 \times$.
- Storm gating & capping: cap at $H_{s,\text{cap}}$ or M_{trip}; auto edge-trim on exceedance; enforce hysteresis to avoid chatter.
- CBM analytics: watch $P95(\Delta M_{\text{eng}})$, slip duty, and reset fails; pre-emptively swap sprag cartridges and bumpers when trends breach thresholds.
- Detailing: generous weld radii, UT/MPI at hot spots, composite bushings tolerant to debris, sealed housings with labyrinths.

9.3 Interannual variability of storm seasons; portfolio siting

What it is. Heavy-tailed climates exhibit 20–40% year-to-year variance in storm energy and hours ≥ deploy. Single-site portfolios can suffer lean seasons.

Impacts

- Revenue volatility: AEP $_d$ swings can stress debt service if contracts are energy-only.
- Under-utilization: several mild years may delay LCOE crossover vs. alternatives.

Mitigations

- Diverse microclimates: distribute units across uncorrelated storm regimes (headlands vs. gap-exits; different exposures). Expect volatility drop ~$1/\sqrt{N}$ with low correlation.
- Contract structure: availability-based or storm-window PPAs (commit kW when $H_s \geq H_{s,\text{deploy}}$); include value adders for resilience (black-start, ramp control).

- Adaptive thresholds: seasonal EVT fits update $H_{s,\text{deploy}}$, $H_{s,\text{cap}}$ to maximize kWh/event within shock/thermal limits.
- Hybridization: share DC bus with battery/supercaps; time-shift bursts into feeder scarcity windows to stabilize cash flow.
- Option value framing: treat assets as contingent capacity (insurance-like) that pays off disproportionately in harsh years; price with historical tails, not mean seas.

Bottom line. The concept trades baseload capture for storm-tail monetization. The main risks—low duty, mechanical shock/fatigue, and seasonal variance—are real but tractable with tail-first siting, compliance + gating, and portfolio/contract design that values what the system actually provides: energy and capacity precisely when the coast needs them most.

10. Roadmap and Future Work

10.1 Multi-flap counterphase arrays and shared inertia buses

Objective: raise duty within deploy windows, reduce ripple, and add fault tolerance.

- Two-flap module (180° counterphase).
    - Independent one-way PTO per flap into a common bus (mechanical flywheel or hydraulic HP manifold).
    - Phase bias (±10–20°) via unequal return springs so lock-ins hand off smoothly.
    - Target: +50–80% average P during deploy events vs. single flap; DC ripple ↓ to ≤15% with shared inertia.
- Four-flap ring (0/90/180/270°).
    - Tiles the power arc; at least one flap harvesting at all times within storm windows.
    - Graded k_t ladder to avoid simultaneous high-jerk engagements.
    - Target: ≥ 80% harvest duty in deploy windows; engagement shock P95 below $0.5{\cdot}M_{\text{slip}}$.

- Shared inertia buses.
  - Mechanical: multi-sprag inputs → torque combiner → single flywheel + PMG; protects generator from impulse stacking.
  - Hydraulic: multi-flap HP manifold + accumulators → one hydromotor + PMG; check-valves isolate units.
  - KPI: cross-coupled trips < 1 per storm event; bus over-voltage = 0.
- Array controls.
  - Per-flap engage windows offset in angle and time; bus-aware lock arbitration when shock rate rises.
  - Fail-graceful: any flap can reef/park without collapsing array output.

10.2 Active trim via cams/yoke trimmers; bi-directional selective harvest

Objective: widen positive-work window without collapse; capture from either surge direction while rectifying to one generator direction.

- Cam-driven trim.
  - Dual-lobe cam maps flap angle $\theta$to trim angle ϕ: broadside on power arc, edge-on on reset.
  - Detented follower + torsion spring provide passive hysteresis; micro-servo optional for closed-loop tweaks.
  - Target: reset time ↓ 30%; engagement shock ↓ 20%; event kWh ↑ 10–20%.
- Yoke trimmer (line-biased).
  - Short trimmer line with preload spring; low tension → edge-on, high tension → broadside.
  - No collapse required; works with plate or membrane faces.
- Bi-directional selective harvest.
  - Mirror sprags or check-valve pairs so either surge direction can be the harvest stroke; a simple direction cam chooses which side locks.
  - Rectification preserved: generator always spins the same direction.

- Guardrails: never allow both sides to lock concurrently; mechanical interlock or controller veto.

- Advanced option—latching.
  - Short holds near peak torque with phase-predicted release (from recent zero-crossings).
  - Enable only in mid-storm band; always bounded by jerk/thermal caps.
  - Target: +10–15% kWh/event in suitable seas without exceeding shock KPIs.

10.3 Automated tail-mapping, adaptive thresholds, and fleet learning

Objective: self-tune deployment to local storm tails; share learning across sites.

- Tail mapping (per site).
  - Log 10–20 Hz H_s, T_e proxies, $\theta, \dot{\theta}$, M_{hinge}, P(t), shock metrics, limiter duty.
  - Fit rolling Weibull + EVT (peaks-over-threshold) for storm bands; estimate inter-gust spacing and rise-time histograms that inform k_t, c_t and trim.
  - Produce a Tail Map: hours ≥ $H_{s,\text{deploy}}$, f_{tail}, directional spread, debris/icing risk.
- Adaptive deployment policy.
  - Contextual bandit over $\{H_{s,\text{deploy}}, H_{s,\text{cap}}, H_{\text{hyst}}\}$ and trim settings to maximize kWh/event subject to constraints (shock P95, thermal, limiter duty).
  - Safety envelope hard limits cannot be crossed; policy steps change gradually (hysteretic roll-in) to avoid mid-storm surprises.
  - KPI: ≥ 10–15% energy/event gain vs. fixed thresholds in first season.
- Fleet learning.
  - Aggregate anonymized telemetry across headlands, gap-exits, downslope classes; train a meta-policy that proposes priors for new sites.
  - Push over-the-air updates; each unit fine-tunes locally.
  - Outcome: faster commissioning, fewer false deploys, and standardized parts/thresholds by microclimate class.

- Operator tooling.
    - Storm Ops Dashboard: live tail share, predicted deploy windows, shock/thermal headroom, and what-if tuning.
    - Health forecaster: flags impending cartridge swaps (sprag/bearings) from shock trends; schedules service into post-storm lulls.

Milestones (12–24 months).

1. Twin-flap module with shared inertia bus meets duty/ripple targets.
2. Cam/yoke trim validated in tank and at sea (reset ↓ ≥30%, kWh/event ↑ ≥10%).
3. Adaptive policy beats fixed thresholds by ≥10% event energy at two distinct microclimates.
4. Fleet memo defines standardized SKUs (hinge cartridge, sprag pod, trim cam set) and site-class default thresholds.

End state. A family of modular, tail-tuned arrays that plug into coastal feeders and microgrids, harvesting reliably when seas are harsh—simple rectified mechanics on top of learned storm intelligence.

11. Conclusion

11.1 Converting extreme seas from hazard to resource

The heaviest sea states—once treated solely as design threats—become an operating regime when motion is rectified, buffered, and storm-gated. The seabed-hinged, one-way-PTO flap reframes storm energy as a controllable pulse resource: harvest on the power arc, overrun on reset, cap peaks, and fail-safe to edge-on when envelopes are exceeded. By tuning a short compliance chain (k_t, c_t, J_f) and enforcing deploy/cap hysteresis, we contain engagement shocks, protect thermal margins, and deliver grid-friendly power precisely when coastal systems are stressed. In this framing, “extreme” no longer means outage; it means opportunity with guardrails.

11.2 Complementarity with conventional WECs and coastal grids

This concept is not a competitor to continuous-duty WECs; it is a storm-tail complement. Where traditional devices de-tune, bypass, or park, the rectified flap activates, adding kWh and—more importantly—committed kW during scarce hours. On shared interconnects the device raises park-level resilience and capacity factor without demanding new transmission. Its low-RPM mechanics, small visual profile, and limited duty simplify environmental fit. In microgrids, seconds-scale buffers (flywheel/supercaps/accumulators) translate pulsed harvest into ramp-compliant injections, displacing diesel peaks and supporting black-start profiles. Measured not only by energy but by value-weighted contribution, the platform fills a gap conventional fleets leave open.

11.3 From pilots to storm-corridor fleets along energetic coasts

The path is pragmatic: (1) bench compliance tuning; (2) tank calibration (JONSWAP, trim cams, optional latching); (3) a single 8–15 m-depth pilot with hard KPIs (reset ≥ 98%, harvest duty ≥ 60%, ripple ≤ 15%, thermal headroom intact); (4) two-flap counterphase modules on a shared inertia bus; (5) array replication at headlands and gap-exits stitched into storm corridors. Telemetry drives tail maps and adaptive policies that raise event energy without breaching shock caps, while standardized cartridges (hinge, sprag, trim) keep OPEX predictable. The end state is a fleet of modular, tail-tuned units that monetize the most energetic hours of the ocean year—turning coastal hazard into bankable, premium-time power at scale.

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(These references ground the rectified, storm-gated flap concept in established wave climate theory (JONSWAP), hydrodynamics (Cummins/Radiation-diffraction; Morison loads), device exemplars (Oyster, Pelamis), PTO choices (Wells, hydraulic), motion-rectification (MMR/AMMR), and standards (IEC 62600 series).)