Battery-Electric Retrofit of Motorized Fishing Boats on the Odisha Coast: A Duty-Cycle-Driven Techno-Economic Assessment with Shared Solar Shore Charging

Simulation study of two craft archetypes, a landing-centre solar hub, and a field duty-cycle measurement protocol

[1]Saswat Swain, [2]Chandrasekhar Panda, [3]Pravat Satpathy
[1]Ph.D Scholar, [2]Researcher, [3]Researcher
[1]KSOM — KIIT Deemed to be University,
Bhubaneswar, Odisha, India
[2,3]Research and Development Division,
Tekstein Solutions Private Limited, Bhubaneswar, Odisha, India
[1]saswat.mck@gmail.com, [2]contact@chandrasekharpanda.com, [3]analytics.pravat@gmail.com

***Abstract*—Odisha's marine fishery operates about twelve thousand motorized country boats, most of them fibreglass beach-landing craft driven by small two-stroke petrol outboards or wooden gill netters with single-cylinder diesel inboards. Fuel is the largest controllable operating cost, yet no peer-reviewed study located by the authors has assessed battery-electric propulsion for these craft, and no measured duty cycles exist. This paper builds the assessment from physical first principles and states every assumption. Calm-water resistance is computed with the ITTC-1957 friction line plus a residuary term calibrated to the installed power and service speed of each archetype. A phase-structured stochastic duty-cycle generator produces 3,600 trips per case, which drive battery sizing through a mass-spiral fixed point, an hourly simulation of a solar charging hub shared by twenty boats, and a 10,000-draw Monte Carlo techno-economic model. The dominant engineering lever is speed: reducing cruise speed by one knot lowers transit energy by 54 percent because these hulls operate near hull speed, which halves the required battery to about 21 kWh. With locally integrated drives and packs, the outboard craft outside turtle-protection zones returns a median net present value of INR 8.81 lakh per boat and a 3.4-year discounted payback. The result does not survive imported branded hardware, low utilization inside the seven-month turtle-ban zones, or the low fuel burn of diesel inboards, each of which yields a median value near or below zero. A closed-form break-even utilization of 66 trips per year is derived and verified. The findings are simulation-only, and a stratified field logging protocol is specified to replace the synthetic duty cycles before any investment decision.**

***Index Terms*—Electric propulsion, small-scale fisheries, lithium iron phosphate battery, duty cycle, techno-economic analysis, solar charging, Monte Carlo simulation, Odisha.**

I. Introduction

Small-scale fishing on India's east coast runs on liquid fuel bought in small quantities at retail prices. In Odisha, the state fisheries directorate lists 1,741 mechanized, 12,246 motorized and 8,167 non-motorized marine craft [1]. The motorized category is the subject of this paper. In the southern districts of Ganjam and Puri it is dominated by fibreglass beach-landing craft of roughly 9–10 m powered by 9–10 hp outboard motors (OBMs); in the northern deltaic districts of Kendrapara and Jagatsinghpur, wooden plank-built gill netters with 10 hp single-cylinder diesel inboards are common [2], [3]. Petrol sold at INR 108.97 per litre in Bhubaneswar and INR 110.45 in Ganjam in mid-2026 [4], and the state's listed schemes subsidize engine purchase [5]; the authors found no Odisha fuel subsidy for outboard operators.

Battery-electric propulsion is a plausible substitute because these craft make short, repeatable day or night trips and return to a fixed landing point. Three strands of prior work support the idea. Perčić *et al.* performed life-cycle and life-cycle-cost assessments of all-electric purse seiners and trawlers and identified lithium iron phosphate (LFP) as the preferred chemistry on both environmental and economic criteria [6]. A modelling study for the U.S. Department of Energy found that a plug-in parallel hybrid would let a 46-ft Alaskan salmon troller cut its fuel use by about 80 percent [7]. Octaviani *et al.* sized a battery for 3-GT *Sandeq* boats in West Sulawesi and estimated 1.8–7.9 t of avoided CO_2 per boat per year, while reporting that investment cost remained prohibitive [8].

None of these studies addresses the Indian east-coast fleet, and none is built on measured duty cycles of the target craft. The closest Indian work is a non-peer-reviewed issue brief for Kerala that reports a 60 percent lower total cost of ownership for solar-assisted electric boats but does not publish the trip energy, battery size or cost inputs behind that figure [9]. A literature search by the authors found no peer-reviewed Odisha study. This suggests, but does not prove, a gap; grey literature from state agencies may exist that was not indexed.

The paper therefore asks four questions. Q1: how much energy does a representative trip need, and how sensitive is that to the way the boat is operated? Q2: what battery does each archetype need once the extra mass of the battery is accounted

for? Q3: can a shared landing-centre solar array supply that energy across the year, given Odisha's monsoon and its seasonal fishing bans? Q4: under which cost, utilization and financing conditions does conversion pay back for the owner?

The contributions are:

(1) a physics-anchored, phase-structured duty-cycle model for two Odisha craft archetypes whose output schema matches a field logger, so that measured traces can replace synthetic ones without code changes;

(2) battery sizing with an explicit mass-spiral fixed point and a range-adaptive speed governor, showing that cruise speed, not distance, sets battery size for hulls operated near hull speed (Proposition 2);

(3) an hourly model of a shared solar hub and a demand–resource coincidence factor that quantifies the penalty of the turtle-ban calendar, which concentrates fishing in the monsoon months (Proposition 3, partially confirmed);

(4) a Monte Carlo techno-economic assessment across archetype, regulatory zone, hardware sourcing and financing, with a closed-form break-even utilization verified against the full model (Proposition 1);

(5) explicit reporting of unfavourable results and ablations, and a stratified measurement protocol with sample-size targets for the field phase.

II. Related Work

Table I summarizes the studies closest to this work. Two methodological threads are visible. Ship-scale studies use life-cycle assessment and life-cycle costing with measured or design operating profiles but treat the charging infrastructure as an exogenous grid [6], [10]. Small-boat studies, including the Sandeq work [8] and the Central Institute of Fisheries Technology solar boat for reservoirs [11], use a constant average power and a cubic speed law, which cannot represent the strongly non-cubic resistance of short, beamy hulls run near hull speed. Asokan *et al.* measured fuel-use intensity across 24 small vessels on India's south-east coast and documented wide variation between craft and engine types [12], which is a warning against relying on a single average trip. No study couples a vessel energy model to a shore charging model under a regulatory fishing calendar, which is the coupling that matters for Odisha.

TABLE I
Comparison of closely related studies

Study	Vessel / region	Energy basis	Charging model	Economics	Main limitation for Odisha use
Perčić et al. 2024 [6]	Purse seiner, trawler; Croatia	Vessel operating profiles	Grid, exogenous	LCA + LCCA; LFP best	Large steel vessels; no small-craft duty cycle
Perčić et al. 2022 [10]	Ro-ro ferries; Croatia	Route schedule	Grid, exogenous	LCA + LCCA	Ferry duty cycle is deterministic
NREL/ALFA 2023 [7]	46-ft troller; Alaska	Fleet operational data	Hydro grid at dock	Retrofit planning	Hybrid, not full electric; news release, not peer-reviewed
Octaviani et al. 2023 [8]	3-GT Sandeq; Indonesia	Cubic law, mean power	Shore PV, unsized	Operating cost only	Capital cost excluded from payback
Ghosh et al. 2023 [9]	Motorized boats; Kerala	Not reported	Solar-assisted	TCO (60% lower)	Inputs not published; not peer-reviewed
Asokan et al. 2023 [12]	24 small vessels; SE India	Measured fuel use	—	—	Combustion only
This work	FRP OBM craft and wooden inboard gill netter; Odisha	Calibrated resistance + stochastic phases	Hourly shared PV hub, bans	MC NPV, payback, MAC	Simulation-only; duty cycles synthetic

LCA: life-cycle assessment; LCCA: life-cycle cost assessment; TCO: total cost of ownership; MC: Monte Carlo; MAC: marginal abatement cost.

III. Problem Statement and Scope

Two archetypes are modelled. Archetype A is the Ganjam/Puri *chotta fibre* beach-landing craft: a 9.5 m fibre-reinforced plastic hull with a 9.9 hp two-stroke petrol OBM, a crew of six and day trips with gill nets up to about 10 km offshore [2], [3]. It is launched through surf and beached on return. Archetype B is the Kendrapara single-cylinder gill netter: an 11 m wooden carvel hull with a 10 hp diesel inboard, a crew of six, night drift-gill-netting 5–10 km offshore, and mooring in creeks rather than beaching [2].

Two regulatory zones are modelled. In zone N, outside turtle-protection areas, the only closure is the uniform east-coast ban from 15 April to 14 June. In zone T, within 20 km of the Dhamra, Devi and Rushikulya river mouths, motorized fishing is also prohibited from 1 November to 31 May to protect olive ridley turtles [13], [14]. Some reports indicate that small craft are tolerated close inshore during the turtle ban [15]; the strict reading is used here and is therefore a lower bound on zone-T utilization.

Every input is labelled in the released code as sourced (S), derived (D), assumed (A) or calibrated (C). Assumed values are carried as distributions in the Monte Carlo analysis. The engineering constraints are a beach-launch peak thrust for archetype A, a battery that must fit the payload margin of a small hull, saline and cyclone-exposed shore infrastructure, and owners whose cost of capital ranges from subsidized Kisan Credit Card loans to informal credit [9].

IV. Proposed Methodology

Fig. 1(a) shows the physical system and Fig. 1(b) the analysis chain. Each stage passes a distribution, not a point estimate, to the next.

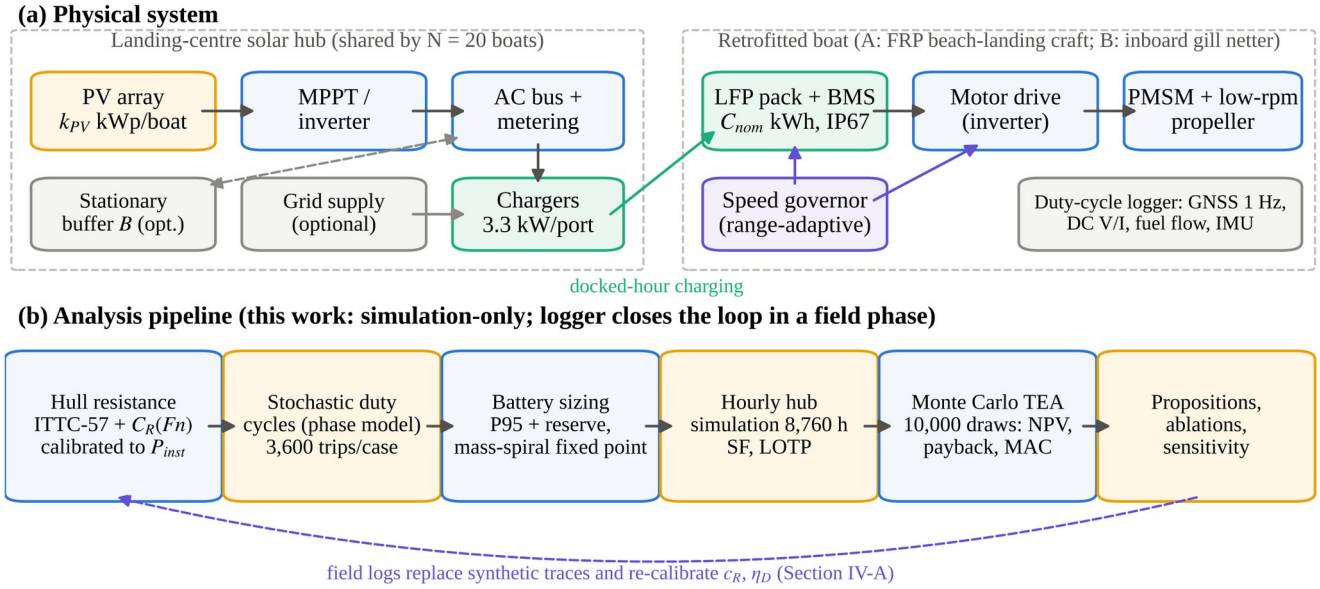


Fig. 1. (a) System architecture: a landing-centre solar hub shared by twenty boats charges each boat's LFP pack during docked hours; a range-adaptive governor limits cruise speed when the state of charge cannot cover the remaining trip. (b) Analysis pipeline. The duty-cycle logger is part of the proposed field phase; all results in this paper are simulated.

A. Duty-Cycle Measurement Protocol (Proposed, Not Executed)

The model is designed so that its weakest component, the synthetic duty cycle, can be replaced by measurement. Table II lists the logger channels. A stratified sample of 24 boats (12 per archetype, split across two districts each) is logged over three seasons: north-east monsoon, pre-monsoon and south-west monsoon. The synthetic ensemble gives a coefficient of variation of trip fuel use of 0.34–0.38; a conservative design value of 0.45 is adopted because field data are usually more dispersed. Estimating the stratum mean within ±10 percent at 95 percent confidence needs $n \geq (1.96 \times 0.45/0.10)^2 \approx 78$ trips per archetype and season, or about 470 trips in total. Speed trials on four boats per archetype at three throttle settings provide the speed–fuel pairs needed to re-estimate the calibrated residuary coefficient and the propulsive efficiency.

TABLE II
LOGGER CHANNELS FOR THE FIELD PHASE

Channel	Sensor	Rate	Use in model
Position, speed over ground	GNSS	1 Hz	Phase segmentation, distance
Fuel flow (baseline boats)	Positive-displacement meter; tank dip per trip	Event / trip	Fuel per trip, SFC map
Engine speed	Inductive or optical pickup	1 Hz	Load estimate
Motion	3-axis IMU	10 Hz	Sea-state margin
Battery V, I, SOC (pilot e-boat)	Shunt + BMS CAN	10 Hz	Direct energy validation
Catch, crew, gear	Landing survey	Trip	Displacement

B. Hull Resistance and Calibration

Total calm-water resistance is decomposed in the usual way,

$$R_T = \tfrac{1}{2}\,\rho S V^2\,[(1+k)C_F(Re) + C_R(Fn)], \tag{1}$$

where ρ is seawater density, S the wetted surface from Mumford's approximation $S = 1.7LT + \nabla/T$, V the speed through water, $1+k = 1.2$ an assumed form factor, Re and Fn the Reynolds and Froude numbers based on waterline length L [16]. The friction coefficient follows the ITTC-1957 line,

$$C_F = 0.075 / (\log_{10}Re - 2)^2. \tag{2}$$

No resistance data exist for these hulls, so the residuary coefficient is given an assumed shape and a calibrated scale,

$$C_R = c_R\,(Fn / 0.35)^p, \tag{3}$$

with $p = 4$ in the base case and 3 and 6 as ablations. The scale c_R is the root of

$$R_T(V_s)\,V_s = 0.85\,\eta_D\,P_{inst}, \tag{4}$$

which states that at the documented service speed V_s the engine delivers 85 percent of its installed power P_{inst} through an overall propulsive efficiency η_D. This anchors the curve to the one operating point that is reasonably known, the installed engine; it is a calibration, not a validation. For the OBM craft $\eta_D = 0.40$ is assumed, reflecting the small, high-speed propeller and gearcase losses of outboards [17]; for the inboard, 0.475. The electric drive is assigned 0.92 motor, 0.97 inverter and 0.55 propeller efficiency, giving $\eta_{D,e}$ of 0.49 and 0.48 for A and B; the improvement for A comes from a larger, slower propeller, an assumption tested in Section VI-G.

C. Stochastic Duty-Cycle Model

A trip is a sequence of phases, each with a duration and a controlled speed. Archetype A: surf launch at full power (4 min), outbound transit at cruise speed over a log-normal distance (median 9 km, clipped to 2–35 km), net setting at 3 kn, soak with the engine off (2.5±0.7 h), hauling at idle or 1 kn, a second set with probability 0.4, loaded return and surf landing. Archetype B: outbound transit (median 8 km), setting, a drift soak of 6±1.5 h with two repositioning manoeuvres, hauling and return. The catch, drawn from a uniform range consistent with logged beach-landing-craft trials [18], adds displacement on the way home. A monthly added-resistance margin m (10–32 percent, highest in the south-west monsoon) scales R_T. Departure times (04:00 for A, 15:00 for B) are retained because they decide when a boat is docked and can charge.

For the conventional engines, fuel flow at brake power P_B is

$$\dot{m}_f = s_f\,P_{inst}\,[a + (1-a)\,P_B/P_{inst}], \tag{5}$$

with rated specific consumption s_f of 0.67 L/kWh for the two-stroke OBM and 0.335 L/kWh for the diesel, from FAO guidance of 0.5 and 0.25 L per horsepower-hour [17], and idle fraction a of 0.12 and 0.10. For the electric drive, battery power is

$$P_{bat} = R_T V / (\eta_{D,e}\eta_{dis}) + P_{hotel}, \quad (6)$$

with discharge efficiency 0.97 and a 60 W hotel load for lights, GNSS, radio and echo-sounder. During surf phases the electric drive must supply the same effective thrust power as the OBM at full throttle, which sets the peak motor rating.

D. Battery Sizing, Mass Spiral and Speed Governor

The nominal capacity covers the zone-weighted 95th-percentile trip energy E_{95} with a 20 percent reserve at end of life:

$$C_{nom} = E_{95}\,(1+r) / (\delta\sigma_{EOL}), \quad (7)$$

with usable depth of discharge $\delta = 0.8$ and end-of-life state of health $\sigma_{EOL} = 0.8$. Because E_{95} depends on displacement and displacement depends on the pack mass $\mu\, C_{nom}$ (μ = 9 kg/kWh), sizing is a fixed point,

$$C^{(i+1)} = \Phi(\Delta_0 + \mu\, C^{(i)} - m_{removed} + m_{motor}), \quad (8)$$

solved by Algorithm 1. Trips that still exceed the usable energy are handled by a governor that lowers cruise speed until the transit energy fits; the fraction of such trips and the speed they need are reported.

Algorithm 1. Mass-spiral battery sizing with speed governor

Input: archetype k, zone z, policy speed V_c, tolerance ε = 1 kg
1: $\Delta m \leftarrow m_{motor} - m_{removed}$
2: repeat
3: simulate 300 trips per month at V_c, displacement $\Delta_0+\Delta m$
4: $E_{95} \leftarrow$ zone-weighted 95th percentile of trip energy
5: $C \leftarrow E_{95}(1+r)/(\delta\sigma_{EOL})$; $\Delta m' \leftarrow m_{motor} - m_{removed} + \mu C$
6: if $|\Delta m' - \Delta m| < \varepsilon$ then break; $\Delta m \leftarrow \Delta m'$
7: for each trip with $E > C\delta\sigma_{EOL}$: bisect V on transit energy = budget
Output: C, governor fraction, required speeds
Cost: O(I·N·K) for I iterations, N trips, K phases; memory O(N).

E. Shared Solar Hub Model

A hub at the landing centre serves $N_b = 20$ boats through 3.3 kW chargers. PV output in hour h is

$$P_{PV}(h) = k_{PV} N_b\, G(h)/1000 \cdot PR, \quad (9)$$

where k_{PV} is the array size per boat in kWp, PR = 0.75 covers temperature, wiring and salt soiling, and $G(h)$ distributes a daily irradiation over a half-sine between sunrise and sunset at latitude 19.8°N. Daily irradiation is the monthly mean multiplied by a log-normal clearness factor whose coefficient of variation is 0.12 in the dry season and 0.35 in the south-west monsoon. The monthly means (annual average 5.0 kWh/m^2/day) are an assumed coastal profile and must be replaced by a satellite point extract before submission. Each hour, PV charges docked boats in order of lowest state of charge, any surplus goes to an optional stationary buffer, and the rest is curtailed. In grid-tied operation the grid tops up only the energy a boat needs for its next departure; the solar fraction is

$$SF = 1 - E_{grid} / (E_{trips}/\eta_{chg}). \quad (10)$$

In off-grid operation a departure without enough energy is counted as lost, and the loss-of-trip probability (LOTP) is the ratio of lost to attempted trips. Fishing on a legal day occurs with a month-dependent participation probability of 0.45–0.72 (assumed).

F. Techno-Economic Model

The base framing is replacement at end of engine life: the owner must buy propulsion at $t = 0$ either way. The net present value of switching is

$$NPV = -(\Delta K_0) + \Sigma_{t=1}^{T} (c_{conv,t} - c_{el,t})(1+r_d)^{-t} + \Delta Res(1+r_d)^{-T}, \quad (11)$$

with horizon $T = 15$ years and real discount rate r_d. Conventional costs are fuel (with real escalation), two-stroke oil at 2 percent of fuel volume, maintenance and engine replacements. Electric costs are grid energy, maintenance, hub operation, and battery replacement when either calendar life or rated throughput is exhausted, with replacement packs cheaper by a real decline rate. Residual values are straight-line. The levelised cost of a trip and the marginal abatement cost are

$$LCOT = PV(costs) / PV(trips), \quad MAC = -NPV / PV(\Delta CO_2), \quad (12)$$

where avoided CO_2 uses 2.31 kg/L for petrol and 2.68 kg/L for diesel, 0.727 tCO_2/MWh for grid electricity [19], and charges battery manufacturing emissions (50–100 kgCO_2e/kWh, assumed) up front. Table III lists the archetype inputs and Table IV the economic distributions. Two hardware regimes are compared: branded imported motors and packs, priced from a 10 kW outboard at about USD 8,000 [20] and marine packs near USD 570/kWh; and locally integrated hardware, whose pack cost is set at about 2.4 times the 2025 global average LFP pack price of USD 81/kWh [21] to cover marine enclosures, battery management and low volume. The local motor cost is a target, not a market quote.

TABLE III
ARCHETYPE PARAMETERS

Parameter	A (FRP OBM)	B (wooden IBM)	Tag
Length overall / waterline (m)	9.5 / 8.6	11.0 / 10.0	S / A
Beam, draft (m)	2.0, 0.45	2.6, 0.80	A
Outbound displacement (t)	1.90	5.25	A
Installed power (kW)	7.3 petrol 2-stroke	7.5 diesel	S
Service / slow speed (kn)	6.5 / 5.5	6.0 / 5.0	A
Froude number at service	0.36	0.31	D
Calibrated c_R	0.00769	0.01110	C
η_D conventional / electric	0.40 / 0.49	0.475 / 0.48	A
Fuel price (INR/L)	110.45	101.0	S [4]

TABLE IV
ECONOMIC INPUTS (TRIANGULAR: MODE, LOW, HIGH)

Input	Mode	Range	Tag
Real discount rate	12%	6–20%	A
OBM 9.9 hp price (INR)	1.35 lakh	1.10–1.60	S [5]
Motor, import / local (INR)	7.6 / 1.8 lakh	6.5–9.0 / 1.3–2.6	D / A
LFP pack, import / local (INR/kWh)	54,000 / 19,000	45–65k / 14–26k	D / A
Battery calendar life (y)	10	7–12	A
Battery cycles to 80% SOH	4,000	3,000–6,000	A
PV, ground-mount (INR/kWp)	50,000	42–60k	A
Grid tariff (INR/kWh)	6.2	4.8–7.5	S [22]
Trips multiplier	1.0	0.85–1.15 (uniform)	A
Fuel-per-trip model error	1.0	0.80–1.20 (uniform)	A

G. Analytical Propositions

Proposition 1 (break-even utilization). If the battery is replaced on calendar life rather than throughput, NPV is affine in annual trips N and is zero at

$$N^{*} = F / (s \cdot A),\ A = \Sigma_{t=1}^{T}(1+r_{d})^{-t}, \quad (13)$$

where s is the operating saving per trip and F the present value of all trip-independent net costs. *Proof sketch:* with calendar-bound replacement, every cash flow is either independent of N or proportional to it, so NPV = $sAN - F$. The condition holds whenever annual throughput is below $\delta C_{nom} n_{cyc}/L_{cal}$, which is satisfied here by a factor of about six.

Proposition 2 (speed elasticity of battery size). For a transit distance d, the transit energy ratio between speeds $V_2 < V_1$ is exactly

$$E(V_2)/E(V_1) = (V_2/V_1)^{n_{m}-1}, \quad (14)$$

where n_m is the mean, over $\ln V$, of the local exponent $n_{eff} = \mathrm{d}\ln P_E/\mathrm{d}\ln V$. *Proof:* $E = R_T d/\eta$ and $\ln R_T = \ln P_E - \ln V$; integrating $n_{eff} - 1$ over $\ln V$ gives the result. Because E_{95} is transit-dominated, battery size inherits this elasticity.

Proposition 3 (seasonal coincidence penalty). Define the coincidence factor $\kappa = \Sigma_m D_m H_m/(\Sigma_m D_m \cdot H_{avg})$, the demand-weighted mean irradiation H_m relative to its annual mean H_{avg}, with D_m the fishing intensity of month m. To first order, if surplus generation on one day cannot serve another, the PV needed for a fixed solar fraction scales as $1/\kappa$. The proposition is stated as a hypothesis and tested against the hourly model, because boat batteries do carry energy between days.

V. SIMULATION SETUP

All models are implemented in Python 3 with NumPy 2.5, SciPy 1.18 and Matplotlib 3.11 on a single-core Linux container. The global seed is 20261023. Each duty-cycle ensemble has 300 trips per calendar month (3,600 per case); the hub model runs 8,760 hours for 20 boats over a grid of 8 PV sizes and 4 buffer sizes, grid-tied and off-grid; the techno-economic model uses 10,000 Monte Carlo draws per scenario with a common random-number stream across scenarios. The complete pipeline runs in about 27 s. Code, parameters with source tags, logs and figure scripts are released as a reproducibility bundle. Sixteen scenarios are evaluated: the full factorial of archetype (A, B), zone (N, T) and hardware (local, import) with slow-steaming as the base operating policy, plus seven variants for speed policy, retrofit timing, financing and capital subsidy.

VI. RESULTS AND DISCUSSION

A. Hull Calibration

The calibration places archetype A at $Fn = 0.36$ and B at 0.31 at service speed (Table III), squarely in the region where wave-making resistance rises steeply. Fig. 2(a) shows effective power: 2.48 kW for A at 6.5 kn and 3.03 kW for B at 6.0 kn. Fig. 2(b) shows the local exponent, which is about 5.9 at service speed and falls towards 3 at low speed. A cubic speed law, as used in [8], therefore understates the benefit of slowing down near service speed by a wide margin and overstates the energy of slow manoeuvring.

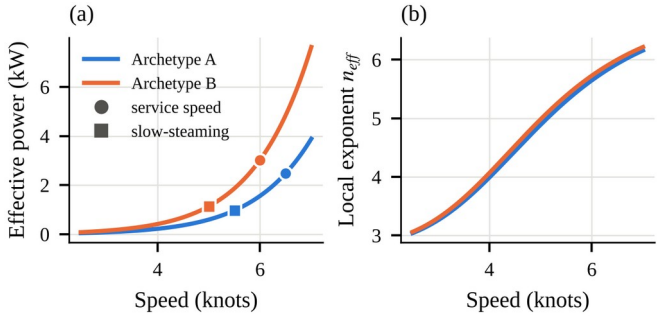


Fig. 2. (a) Calibrated effective power versus speed; circles mark the service speed used for calibration and squares the slow-steaming policy. (b) Local exponent $n_{eff} = \mathrm{d}\ln P_E/\mathrm{d}\ln V$.

B. Trip Energy and Battery Size

At service speed, the median conventional trip of archetype A burns 8.9 L of petrol (95th percentile 16.1 L) over 6.6 h and 19.6 km; B burns 3.9 L of diesel over 9.9 h. The OBM figure is consistent with the order of 1 L/h reported for small kerosene outboards [23]. The diesel figure is low because the engine is assumed off during the drift; a 1989 beach-landing-craft trial with a 9 hp diesel logged about 20 L per 10–11 h night [18], which implies far more engine running. This discrepancy is the largest unresolved uncertainty for archetype B and is a priority for logging.

Electrically, the same trips at service speed need a median of 11.6 kWh for A, so a battery would carry about 14.6 percent of the chemical energy in the petrol it replaces. Fig. 3(b) shows the full distributions. Sizing for the 95th percentile at service speed would need 45.4 kWh and 408 kg on a 1.9 t boat, which is not a practical retrofit. At the slow-steaming speed the requirement falls to 21.5 kWh (193 kg) for A and 20.7 kWh for B (Table V). The mass spiral converges in three iterations; ignoring it under-sizes the pack by 3.6 percent. At end of life, 1.7 percent of zone-N trips for A would need the governor, at a median cruise speed of 5.36 kn, and none would be infeasible. The peak battery power of 6.2 kW occurs in the surf launch, so a motor of about 8 kW peak is sufficient.

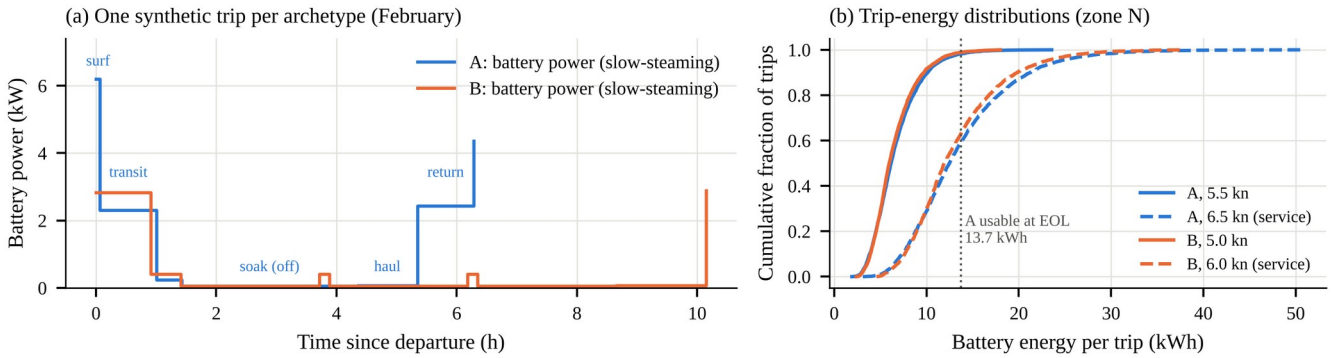


Fig. 3. (a) Battery power for one synthetic trip of each archetype under slow-steaming; phases are labelled for A. (b) Cumulative distributions of battery energy per trip in zone N at slow-steaming (solid) and service speed (dashed); the dotted line is archetype A's usable capacity at end of life.

TABLE V
BATTERY SIZING (SLOW-STEAMING UNLESS STATED)

Case	P50 (kWh)	P95 (kWh)	P99 (kWh)	C_{nom} (kWh)	Mass (kg)	Governed trips
A, zone N	6.1	11.5	14.7	21.5	193	1.7%
A, zone T	6.6	12.2	15.2	22.9	206	1.4%
B, zone N	5.9	11.1	13.6	20.7	187	1.2%
B, zone T	6.5	11.8	14.6	22.1	199	1.2%
A, N, service speed	12.3	24.2	31.6	45.4	408	1.7%
B, N, service speed	11.8	22.6	28.9	42.4	382	1.5%

Governed trips: share of trips needing a speed reduction at end-of-life capacity; no trip was infeasible in any case.

C. Effect of Speed Policy

For A, the mean exponent between 5.5 and 6.5 kn is $n_m = 5.63$, so Proposition 2 predicts a transit-energy ratio of 0.462. The stochastic ensemble, which includes sea margins and catch, gives 0.462. For B the prediction is 0.451 and the ensemble 0.461; the small gap reflects the heavier inbound displacement. In calm water the proposition is an identity, so the useful check is the ensemble agreement. Whole-trip energy falls less, to 0.51 of its service-speed value for A, because hauling and surf phases are unchanged. The cost is 20 extra minutes per trip for A, which may matter for catch freshness and market timing; that cost is not monetised here.

D. Solar Hub Performance

The assumed profile gives 1,389 kWh/kWp per year. Fig. 4(a) shows why the calendar matters: in zone T, fishing is confined to mid-June through October, the cloudiest months, and $\kappa_T = 0.885$ against $\kappa_N = 0.972$. Proposition 3 therefore predicts that zone T needs 9.9 percent more PV per unit of daily demand for the same solar fraction. The hourly model gives 5.9 percent at an 80 percent solar fraction. The direction is confirmed and the magnitude is roughly halved, because idle boats charge on non-fishing days and carry that energy forward. The proposition is thus an upper bound, not an equality.

Fig. 4(b) shows that about 1.5 kWp per boat brings the grid-tied solar fraction to 99 percent (98.8 percent in zone N) for archetype A in either zone. The least-cost grid-tied design under the base tariff is smaller, 1.0 kWp per boat with no stationary buffer, reaching a solar fraction of 85.7 percent in zone N, because grid energy at INR 6.2/kWh is cheap relative to the annualised cost of unused panels. Two results were not expected. First, a stationary buffer adds almost nothing: at 2 kWp per boat, off-grid LOTP is 1.7 percent without a buffer and 1.4 percent with 5 kWh per boat, because both archetypes are docked through the solar day and their own packs act as storage. Second, the off-grid LOTP does not fall below about 1.5 percent however much PV is added. That floor is set by trips longer than the battery covers, not by the solar resource, and is removed by the speed governor.

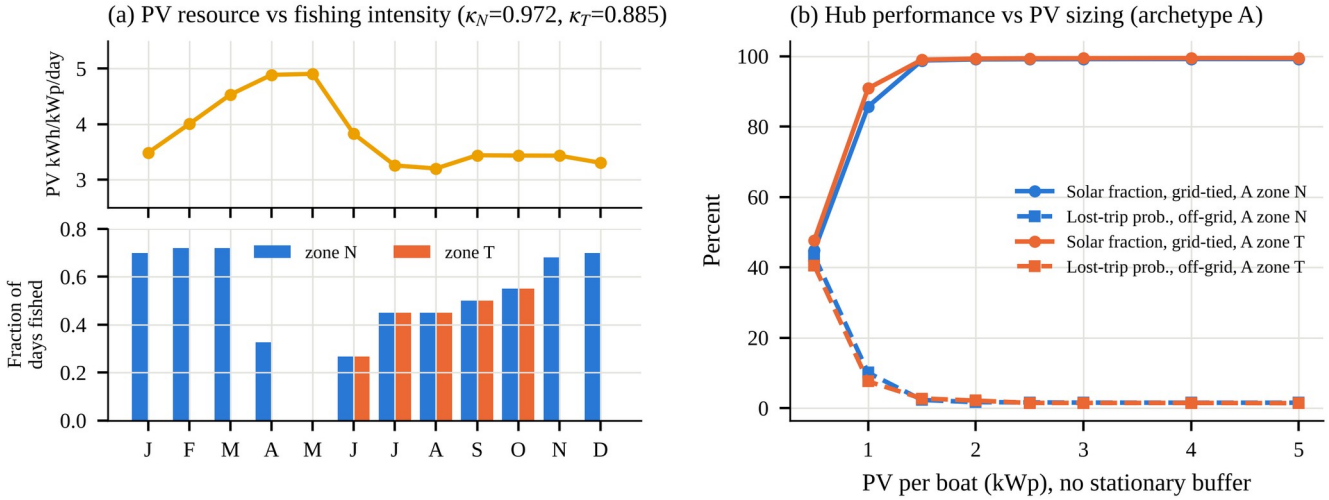


Fig. 4. (a) Monthly PV yield per kWp (upper) and the fraction of days fished in each zone (lower); zone T fishes only in the monsoon window. (b) Grid-tied solar fraction (solid) and off-grid loss-of-trip probability (dashed) for archetype A versus PV per boat, without stationary storage.

E. Economic Outcomes

Fig. 5 and Table VI summarise the Monte Carlo results. Only one scenario in the base matrix is robustly favourable: archetype A in zone N with locally integrated hardware, which has a median NPV of INR 8.81 lakh (P10–P90: 5.00–13.84), a median discounted payback of 3.4 years and a positive NPV in

all draws. Its levelised cost per trip falls from INR 1,422 to 690. The up-front outlay is about INR 6.98 lakh including an INR 0.87 lakh hub share, against INR 1.35 lakh for a new OBM, so financing, not lifetime economics, is the binding barrier for an owner.

The same boat inside a turtle zone makes about 68 trips a year rather than 184 and is a coin-flip, with 53.3 percent of draws positive. Archetype B is also marginal in zone N (median INR -0.21 lakh), not because the electric boat costs more but because a diesel inboard that is switched off during the drift burns little fuel; its per-trip cost is roughly equal under both technologies. With imported branded hardware every scenario has a negative median, and the outboard craft in zone N is positive in only 5.0 percent of draws. These are the main negative results of the study.

Policy changes the picture. A 60 percent capital subsidy, which mirrors the existing Odisha engine-motorisation scheme for SC/ST beneficiaries [5], combined with a 7 percent loan rate, turns all three cases to which it was applied positive, including zone T (median INR 6.08 lakh) and imported hardware in zone N (INR 9.52 lakh). Operating at service speed instead of slow-steaming cuts the median NPV of the best case to INR 3.22 lakh and makes 15.5 percent of draws negative, because the battery doubles. A 20 percent informal cost of capital halves the NPV but leaves it positive. An early retrofit, which forgoes the credit for avoiding a new OBM purchase, costs about INR 0.9 lakh of NPV.

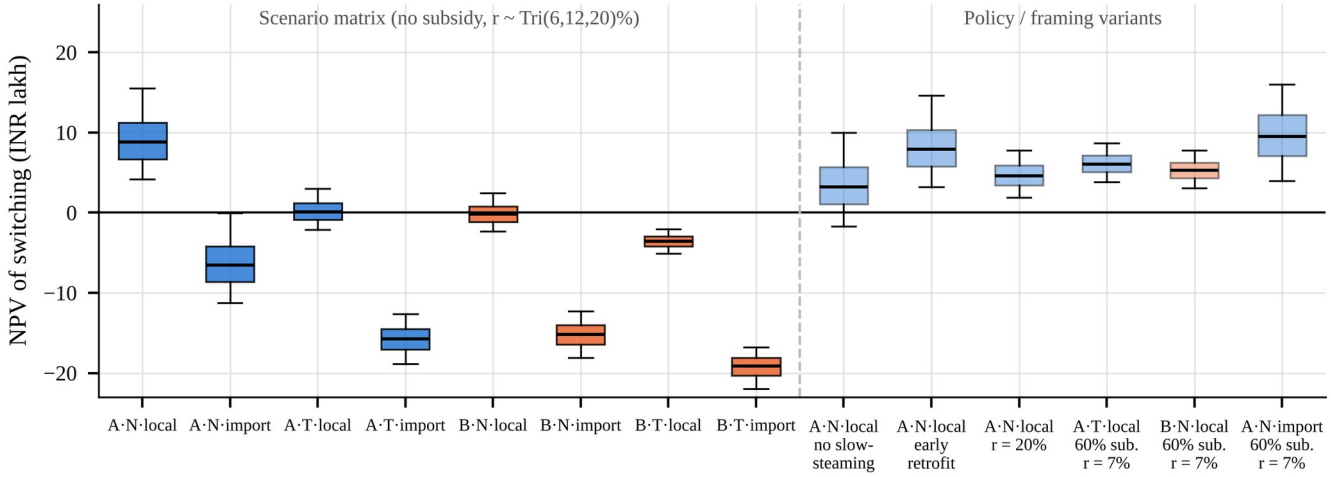


Fig. 5. Distribution of NPV of switching per boat (box: P25–P75; whiskers: P5–P95; line: median). Left: base matrix without subsidy, discount rate triangular 6–12–20 percent. Right: operating-policy, retrofit-timing, financing and subsidy variants.

TABLE VI
MONTE CARLO ECONOMIC RESULTS PER BOAT (10,000 DRAWS; NPV IN INR LAKH)

Scenario	Trips/y	NPV P10	NPV P50	NPV P90	P(NPV>0)	Payback P50 (y)	CO_2 avoided (t/y)	MAC P50 (INR/tCO_2)
A-N-local	184	5.00	8.81	13.84	100.0%	3.4	3.63	-39,600
A-N-import	184	-10.39	-6.53	-1.62	5.0%	—	3.63	29,400
A-T-local	68	-1.67	0.13	2.30	53.3%	—	1.14	-2,300
A-T-import	68	-18.18	-15.76	-13.32	0.0%	—	1.14	281,300
B-N-local	184	-1.89	-0.21	1.83	44.1%	—	1.71	2,200
B-N-import	184	-17.49	-15.20	-12.91	0.0%	—	1.71	158,900
B-T-local	68	-4.75	-3.55	-2.37	0.0%	—	0.39	334,500
B-T-import	68	-21.33	-19.13	-17.22	0.0%	—	0.39	1,858,300
A-N-local, service speed	184	-0.78	3.22	8.31	84.5%	6.6	3.26	-18,200
A-N-local, r = 20%	184	2.42	4.60	7.07	100.0%	4.0	3.63	-31,100
A-T-local, 60% subsidy, r = 7%	68	4.28	6.08	8.10	100.0%	2.3	1.14	-67,200
B-N-local, 60% subsidy, r = 7%	184	3.52	5.27	7.22	100.0%	2.4	1.71	-36,500
A-N-import, 60% subsidy, r = 7%	184	5.05	9.52	14.61	100.0%	4.0	3.63	-29,900

Payback shown only when at least half the draws pay back within 15 years. Negative MAC indicates abatement with a net saving. CO_2 avoided is net of grid electricity and battery manufacturing emissions.

F. Sensitivity and Break-Even

Fig. 6 ranks the inputs for the favourable case. The discount rate moves NPV between INR 4.5 and 14.8 lakh, followed by fuel use per trip and trips per year, which act through the same channel, the annual fuel bill. Both are model-derived here and both would be measured in the field phase. Battery price ranks sixth, and battery cycle life has no effect because calendar ageing ends the pack's life first.

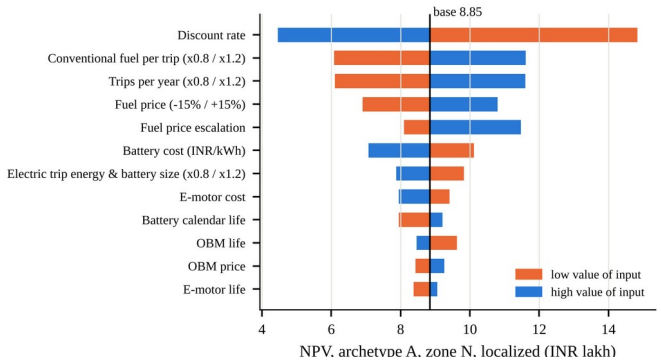


Fig. 7(b) verifies Proposition 1. NPV is exactly linear in trips over 20–320 trips per year; the closed-form slope sA matches the numerical slope to machine precision, and the break-even utilization is 66 trips per year for A with local hardware, 271 with imported hardware, and 184 for B. The last value coincides with B's zone-N utilization, which explains its coin-flip outcome. Fig. 7(a) maps NPV over petrol price and pack cost: at the base petrol price, conversion of A stays positive up to a pack cost of about INR 54,000/kWh, close to the branded import price, provided the motor is locally integrated. The motor price, not the pack price, separates the import regime from the local one.

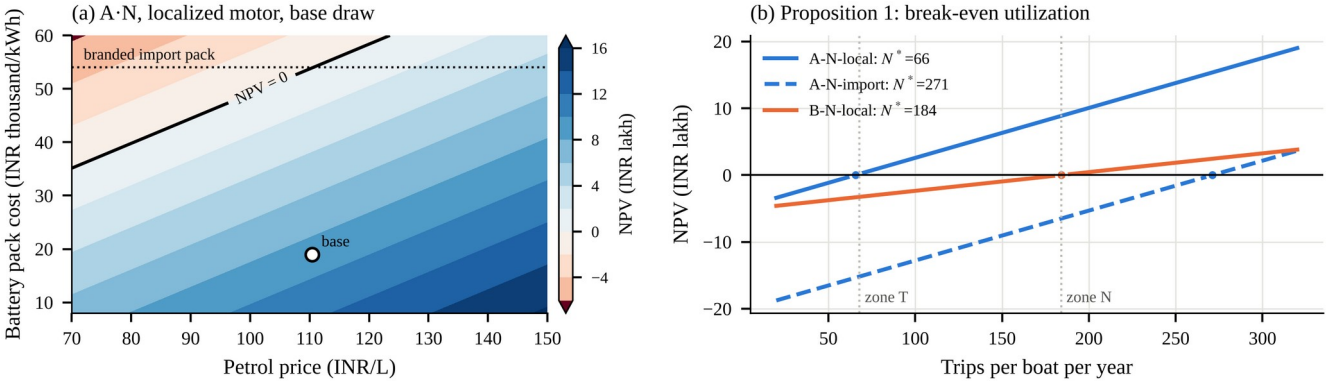


Fig. 7. (a) NPV for archetype A, zone N, local motor, over petrol price and battery pack cost; the black line is NPV = 0. (b) NPV versus trips per year with the analytic break-even points of Proposition 1; dotted lines mark median utilization in zones T and N.

G. Ablations

Table VII reports ablations on archetype A, zone N, local hardware, base draw. The result is robust to the assumed shape of the residuary curve, because calibration pins the curve at service speed and the slow-steaming point is close by. Removing the electric propeller's efficiency advantage raises the battery by 22 percent and lowers NPV by 12 percent. A 50 percent higher sea margin increases NPV, because the conventional boat's fuel use rises more in money terms than the electric boat's battery cost. Removing slow-steaming is the only change that alters the conclusion materially.

TABLE VII
ABLATIONS (ARCHETYPE A, ZONE N, LOCAL, BASE DRAW)

Configuration	E_{95} (kWh)	C_{nom} (kWh)	NPV (lakh)
Base (p = 4, slow-steaming)	11.5	21.5	8.85
Residuary shape p = 3	12.5	23.5	8.64
Residuary shape p = 6	9.8	18.3	9.10
Electric η_D equal to OBM	13.9	26.1	7.80
Sea margin ×1.5	12.3	23.0	9.03
No slow-steaming	24.2	45.4	3.42
Mass spiral ignored	11.0	20.7	under-sized

VII. COMPARATIVE ANALYSIS

Table VIII places the results beside prior work. The per-trip energy of archetype A at slow-steaming, about 6 kWh at the median, is comparable to the 9.0 kWh daily demand computed for the Sandeq boat [8], which runs longer at lower average power. The NREL hybrid and the Croatian fishing vessels are not comparable in scale, but their conclusions agree with this study on two points: LFP is the appropriate chemistry, and electrification pays only where the operating profile is short, repeatable and fuel-intensive. Unlike [8] and [9], this study includes capital cost, battery replacement and shore infrastructure in the payback, and it reports the scenarios that fail.

TABLE VIII
COMPARISON WITH PRIOR STUDIES

Metric	This work (A, N)	Sandeq [8]	Kerala [9]	Croatia [6]
Craft	9.5 m FRP, 7.3 kW OBM	8.6 m wood, 4.8 kW	Motorized boats	Purse seiner, trawler
Energy basis	Calibrated, stochastic	Cubic law	Not reported	Operating profile
Battery (kWh)	21.5	13.5	n.r.	Ship-scale
Capital in payback	Yes, incl. hub	No	Yes (TCO)	Yes
Charging model	Hourly PV hub	Concept	Solar-assisted	Grid
Unfavourable cases reported	Yes	Capital cost noted	No	Yes

VIII. LIMITATIONS AND THREATS TO VALIDITY

The study is simulation-only and no hardware was built or tested. The duty cycles are synthetic: phase durations, distances, idle behaviour and catch are assumptions derived from qualitative craft descriptions, and the fuel-per-trip results have not been checked against measurement. The hull model is calibrated to a single assumed operating point per archetype, so the steep resistance curve that drives the slow-steaming result rests on the assumption that these boats are normally run near full throttle at about 6.5 kn; if real service speeds are lower, the benefit of slowing down is smaller and the battery larger. The monthly irradiance profile is an assumed coastal profile, not a site extract. Surf launching and beaching with a 190 kg pack, saltwater immersion of electrical equipment, cyclone exposure of the hub, theft and insurance are not modelled. Grid export of curtailed PV is not credited, which is conservative. Catch value, crew wages and the time cost of slower trips are excluded. The electric motor's local cost is a target. All references require independent verification of volume, page and DOI details before submission.

IX. Conclusion

A duty-cycle-driven assessment of battery-electric retrofits for Odisha's motorized fishing boats was developed from a calibrated resistance model, a stochastic trip generator, a mass-spiral battery sizing algorithm, an hourly shared-solar hub model and a Monte Carlo cost model. Under its stated assumptions, the outboard-powered beach-landing craft outside turtle-ban zones is the strongest candidate: about 21 kWh of LFP at a 5.5 kn cruise speed, roughly one kilowatt-peak of shared PV per boat, a median NPV of INR 8.81 lakh and a 3.4-year payback with locally integrated hardware. The case fails with imported branded hardware, is marginal inside turtle zones and for diesel inboard gill netters, and depends heavily on operating at reduced speed. Capital subsidy and concessional finance turned every case to which they were applied positive, including the turtle-zone and imported-hardware cases. The next step is the field phase of Section IV-A: logging 24 boats over three seasons, re-calibrating the resistance and fuel models, and running a single-boat pilot with direct battery telemetry before any fleet programme is designed.

Acknowledgment

[To be completed by the authors.] Data availability: the reproducibility bundle (code, parameters with source tags, results and figure scripts) accompanies this manuscript.

References

[1] Directorate of Fisheries, Government of Odisha, "Odisha fisheries at a glance: general information, 2020–21," published with WorldFish, CGIAR Research Program on Fish Agri-Food Systems. [Online]. Available: digitalarchive.worldfishcenter.org

[2] A. Sridhar and M. Muralidharan, *Marine Fishing Craft and Gear of Odisha*. Bangalore, India: Dakshin Foundation, 2013.

[3] S. K. Roul *et al.*, "Large pelagics fisheries along Odisha coast—An overview," *Marine Fisheries Information Service, Technical and Extension Series*, ICAR-CMFRI, Kochi, India. [Verify authors, issue and year.]

[4] "Petrol, diesel and CNG prices in Odisha," carchhe.com and aajtak.in fuel-price trackers, accessed Oct. 2026.

[5] Fisheries and Animal Resources Development Department, Government of Odisha, "Motorisation of traditional crafts," myScheme portal. [Online]. Available: myscheme.gov.in/schemes/mtc

[6] M. Perčić, M. Koričan, I. Jovanović, and N. Vladimir, "Environmental and economic assessment of batteries for marine applications: Case study of all-electric fishing vessels," *Batteries*, vol. 10, no. 1, Art. no. 7, 2024, doi: 10.3390/batteries10010007.

[7] A. Squires, "Battery-electric fishing vessel marks a sea change for small commercial fishers," National Renewable Energy Laboratory, Golden, CO, USA, news release, Aug. 22, 2023.

[8] N. S. Octaviani *et al.*, "The influence of battery-powered engine on the reduction of carbon dioxide production from fishing boats," *J. Mechatronics, Electr. Power, Veh. Technol.*, vol. 14, no. 2, pp. 208–214, Dec. 2023, doi: 10.14203/j.mev.2023.v14.208-214.

[9] N. Ghosh, A. Soman, H. Kaur, and H. Jain, "How solar-assisted electric boats can empower fishing livelihoods: A Kerala case study," Council on Energy, Environment and Water, New Delhi, India, Issue Brief, Feb. 2023.

[10] M. Perčić, L. Frković, T. Pukšec, B. Ćosić, O. L. Li, and N. Vladimir, "Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation," *Energy*, vol. 251, Art. no. 123895, 2022, doi: 10.1016/j.energy.2022.123895.

[11] Indian Council of Agricultural Research, "CIFT develops a solar powered boat," ICAR news, 2014. [Online]. Available: icar.org.in

[12] K. Asokan *et al.*, "Fuel use in small-scale fishing vessels along the southeast coast of India: A comparative study to ascertain possible reasons and potential recommendations for effective management," *Environ. Monit. Assess.*, vol. 195, no. 2, Art. no. 345, 2023, doi: 10.1007/s10661-023-10962-y.

[13] Fisheries and Animal Resources Development Department, Government of Odisha, "Livelihood support to marine fishermen during fishing ban period," myScheme portal. [Online]. Available: myscheme.gov.in/schemes/lsmfdfbp

[14] "Aid to Odisha fisherfolk doubled for fishing ban to save turtles; Is it enough?" *Down To Earth*, New Delhi, India. [Verify date.]

[15] "Olive ridley turtles arrive near Rushikulya rookery," International Collective in Support of Fishworkers news digest, reproducing *The Hindu*. [Verify date.]

[16] L. Larsson and H. C. Raven, *Ship Resistance and Flow*. Jersey City, NJ, USA: Society of Naval Architects and Marine Engineers, 2010.

[17] Ø. Gulbrandsen, *Fuel Savings for Small Fishing Vessels: A Manual*. Rome, Italy: FAO, 2012.

[18] Bay of Bengal Programme, "Fishing trials with beachlanding craft," FAO/BOBP report AD838E, Madras, India, c. 1990. [Verify title, authors and year.]

[19] Central Electricity Authority, *CO_2 Baseline Database for the Indian Power Sector*, Version 20.0, New Delhi, India, Dec. 2024.

[20] "Four electric boat motors compared," *Boating Magazine*, 2023. [Online]. Available: boatingmag.com [Verify date.]

[21] BloombergNEF, "Lithium-ion battery pack prices fall to USD 108 per kilowatt-hour, despite rising metal prices," press release, New York, NY, USA, Dec. 9, 2025.

[22] Odisha Electricity Regulatory Commission, "Retail supply tariff notification for FY 2025–26," Bhubaneswar, India, Mar. 24, 2025.

[23] Bay of Bengal Programme, "Reducing the fuel costs of small fishing boats," BOBP/WP/27, FAO, Madras, India, 1986. [Verify authors.]