The Blue Fiscal Transition of the Archipelago:

From Consumptive Subsidies to Sovereign Capital Guarantees in Maritime Electrification of Indonesia’s Artisanal Fishing Fleet

Executive Summary

The Republic of Indonesia currently stands at the precipice of a defining structural transformation within its maritime economy. For decades, the nation has maintained a social contract with its coastal communities predicated on the provision of subsidized fossil fuels—specifically Pertalite and Biosolar—to insulate artisanal fishers from the volatility of global energy markets. While this policy has historically served as a critical poverty alleviation mechanism, preserving the purchasing power of millions of households dependent on the *Jukung* fleet, it has calcified into a fiscal burden that erodes the effectiveness of the State Budget (*Anggaran Pendapatan dan Belanja Negara* - APBN) and perpetuates the use of ecologically ruinous propulsion technologies. The status quo represents a "sunk cost" economic model: billions of Rupiah are incinerated annually in the combustion chambers of inefficient two-stroke outboard motors, leaving behind no permanent asset, no productivity gain, and a degraded marine environment.

This comprehensive research report proposes, analyzes, and advocates for a strategic policy pivot: the reallocation of a portion of the maritime fuel subsidy budget into a sovereign Loan Guarantee Fund (LGF). This mechanism is designed to unlock commercial capital for the electrification of the artisanal Jukung fleet, specifically targeting vessels utilizing 15–40 hp outboard motors. By leveraging the specific technical attributes of the "Gempacs" electrification model—characterized by a 2 kWp solar canopy with a critical 2.5-degree aerodynamic slope—and aligning with the intermittent energy profile of drift gill net fishing, the state can transform a perpetual liability into a self-sustaining capital asset.

The analysis provided herein is exhaustive. It dissects the thermodynamics of the two-stroke engine to quantify the magnitude of energy waste; it models the aerodynamic and hydrodynamic interactions of the solar-canopied Jukung to validate safety parameters; and it reconstructs the financial architecture of the *Koperasi* (Cooperative) to demonstrate how government guarantees can bridge the "bankability gap" for artisanal fishers. The findings suggest that by utilizing the People's Business Credit (*Kredit Usaha Rakyat* - KUR) framework under the newly adjusted Regulation of the Coordinating Minister for Economic Affairs Number 1 of 2026, the government can facilitate a cost-neutral transition that doubles fisher income, eliminates maritime emissions, and secures Indonesia’s status as a leader in the global Blue Economy.

1. The Macro-Fiscal Landscape: The Subsidy Trap and the Energy Trilemma

1.1 The Historical Context of Energy Subsidies in Indonesia

Indonesia's relationship with energy subsidies is deeply rooted in its post-independence political economy. As an oil-producing nation for much of the 20th century, cheap fuel was considered a birthright of the citizenry.[1] However, as domestic consumption outpaced production, transforming Indonesia into a net oil importer in the early 2000s, the fiscal logic of these subsidies collapsed. The subsidies, once funded by oil export revenues, began to devour the general budget, crowding out vital investments in infrastructure, education, and health.

In 2024 and 2025, the government continues to grapple with this legacy. Energy subsidies cover electricity, LPG, and crucially, liquid fuels like Pertalite (RON 90) and Biosolar (Diesel).[2] The regulated retail prices are consistently set below the economic cost of supply, creating a "price gap" that the government fills through direct subsidy payments to Pertamina and compensation for lost revenue.[1] This mechanism, while stabilizing inflation, creates a massive distortion. It encourages overconsumption and disincentivizes efficiency. For the artisanal fisher, who operates on razor-thin margins, the subsidized price of IDR 10,000 per liter for Pertalite [3] is a lifeline. Without it, the cost of a fishing trip would double, rendering their livelihood unsustainable under the current technological regime.

However, the "open" distribution system of Pertalite results in significant leakage. Despite attempts to target subsidies, the disparity between the subsidized price and the market price (often IDR 3,000 to 5,000 per liter higher) incentivizes black market trading and ensures that the subsidy benefits the middle class and industrial users as much as, if not more than, the vulnerable poor.[4] The government's attempts to reform this, such as the price hikes in 2014 and 2022, have always been politically fraught, often sparking unrest. The challenge, therefore, is not merely to remove the subsidy but to *transform* it—to find a mechanism that protects the fisher's livelihood without bleeding the state treasury.

1.2 The "Sunk Cost" Trap of the Two-Stroke Engine

The primary vector of this fiscal inefficiency in the maritime sector is the two-stroke outboard motor. This engine architecture dominates the Indonesian small-scale fleet (vessels under 5 Gross Tons) due to its simplicity, high power-to-weight ratio, and low upfront acquisition cost.[5] However, thermodynamically and economically, it is a disaster.

The traditional carbureted two-stroke cycle relies on "scavenging," where the incoming fuel-air mixture pushes the exhaust gases out of the cylinder. Because the intake and exhaust ports are open simultaneously, a significant portion of the fresh fuel charge—up to 30%—escapes directly into the exhaust without ever being burned.[6] This phenomenon, known as "short-circuiting," means that for every 10 liters of subsidized fuel the government pays for, 3 liters are effectively dumped raw into the ocean. This represents a direct transfer of state wealth into environmental pollution.

Furthermore, the thermal efficiency of these engines rarely exceeds 20%. The remaining 80% of the energy content in the fuel is lost as heat and noise. When the government subsidizes Pertalite for a two-stroke Jukung, it is effectively subsidizing entropy. It is paying to heat the atmosphere and poison the marine ecosystem. The fisher, locked into this technology by its low capital cost, is forced to spend 60–70% of their operational expenditure (OPEX) on fuel, trapping them in a cycle of poverty where they work primarily to pay for the gasoline that powers their boat.[7]

1.3 The Strategic Pivot: From OPEX to CAPEX

The central thesis of this report is that the solution to the subsidy problem is not higher prices, but better technology. Electrification changes the economic equation fundamental to fishing. An electric motor has a thermal efficiency of over 90%. It consumes no energy when idling. When paired with a solar canopy—specifically the Gempacs model designed for the tropics—it generates its own fuel.

However, electric propulsion exchanges high variable costs (fuel) for high fixed costs (batteries and motors). The fisher trades a daily payment of IDR 150,000 to the gas station for a one-time payment of IDR 100,000,000 for the equipment. Since the artisanal fisher lacks the capital to make this switch, the state must intervene. But rather than spending money on consumption (fuel subsidies), the state should use its balance sheet to guarantee loans that allow fishers to acquire these capital assets. This shifts government expenditure from a recurring expense to a one-time liability authorization that creates a permanent, productive asset.

2. The Technical Baseline: Anatomy of the Crisis

To design an effective intervention, one must understand the specific technical constraints of the Indonesian artisanal fleet. The "Jukung" is not a uniform vessel, but a class of double-outrigger canoes that has evolved over centuries to navigate the specific hydrodynamics of the archipelago.

2.1 The Jukung Platform Specifications

The typical Jukung involved in this analysis is a vessel of 7 to 11 meters in length, with a narrow hull beam of 0.8 to 1.2 meters. The stability of the vessel is provided entirely by the *katir* (outriggers), which are bamboo poles lashed to arched crossbeams (*ati-ati*).[9]

- **Hull Dynamics:** The slender hull form is highly efficient, requiring relatively low power to reach displacement speeds. However, the outriggers add significant drag at higher speeds and create complex torsional loads on the structure.
- **Operational Range:** These vessels typically operate within 12 nautical miles of the coast, in WPP (Fisheries Management Areas) that are prone to sudden squalls and high surf.[11]
- **Propulsion Class:** The fleet is powered almost exclusively by 15 hp to 40 hp outboard motors. The 15 hp engine is the standard "workhorse," providing enough thrust to punch through the surf zone when launching from beaches—a critical safety maneuver that lower-power alternatives often fail to execute.[12]

2.2 Exclusion of the Ketinting and Diesel Inboards

A critical distinction in this analysis is the explicit exclusion of the *Ketinting* (long-tail) and inboard diesel engines.

- **The Ketinting:** This propulsion system uses a general-purpose agricultural engine (often a Honda or Chinese clone) mounted on a gimbal frame with a long shaft extending directly into the water. While cheap and fuel-efficient compared to a two-stroke outboard, the Ketinting lacks a gearbox (Neutral/Reverse), making it dangerous for precision maneuvering during net setting. Furthermore, the vibration of these engines is incompatible with the sensitive electronics of a solar-electric system without massive structural reinforcement.[13]
  This type of propulsion, is marginal in this study, due to the scarce diffusion of this propulsion method in Indonesia, whereas it usage is limited to the shallow waters of rivers and inland waters.
- **Diesel Inboards:** Small diesel engines are heavy and require a through-hull shaft log and rudder assembly. Retrofitting a traditional fiberglass or wood Jukung for a diesel inboard requires major structural surgery that is often more expensive than the hull itself. The outboard motor, clamped to the transom, is the only viable form factor for a scalable retrofit program.

2.3 The Environmental Toll of the Two-Stroke

The reliance on two-stroke outboards creates a localized ecological crisis. In busy fishing ports like Cilacap or Muncar, the water is often covered in a permanent film of unburned hydrocarbons.

- **Acoustic Pollution:** The high-frequency noise of a two-stroke engine (often exceeding 100 dB) causes hearing loss among fishers [8] and disrupts marine life.
- **Carbon Footprint:** While individual emissions are small, the aggregate footprint of 500,000+ vessels is immense. A single 15 hp two-stroke engine running for 5 hours emits as much pollution as driving a modern car for thousands of kilometers.[15]

3. The Technical Solution: The Gempacs Architecture

The proposed solution utilizes the "Gempacs" integrated ecosystem. This is not merely an engine swap; it is a holistic energy system designed specifically for the Jukung platform. It consists of three integrated subsystems: the electric propulsion train, the solar energy canopy, and the IoT management layer.

3.1 The Propulsion Train: High-Torque Electric Outboards

The system replaces the ICE outboard with a Brushless DC (BLDC) electric outboard rated between 10 kW and 15 kW (equivalent to 15–25 hp ICE thrust).

- **Torque Characteristics:** Unlike an ICE, which needs to rev up to 3000+ RPM to generate peak torque, an electric motor provides instant torque from zero RPM. This is crucial for the Jukung, allowing for immediate power application when navigating breaking waves or correcting drift during net deployment.[16]
- **Efficiency:** The motor operates at >90% efficiency across a wide RPM range. This means that for every kilowatt-hour (kWh) of energy stored in the battery, nearly all of it is converted into thrust, a 4x improvement over the 20% efficiency of the ICE.

3.2 The Solar Canopy: Physics and Geometry

Traditional Indonesian boats (jukung) have long bamboo arms (outriggers) on the sides to keep them steady. These arms make the boat very wide—much wider than a car. This allows Gempacs to install a large solar canopy (up to 2 kW+), light in weight, on a relatively small eight meters boat.

- **Operational Relevance:** A 2 kWp array (approx. 10 m²) operating at a conservative system efficiency of 75% (accounting for heat, cabling, and minor shading) will generate about 7.2 kWh per day, it is enough energy to drive a 10 kW motor at "cruise" power (approx. 3 kW) for nearly 2.5 hours. For a drift gill net fisher who spends hours drifting (charging), this could effectively extend the range to infinity during daylight hours.
- **The 2.5-Degree Solution:**
  - **Minimal Lift/Drag:** At 2.5 degrees, the canopy is effectively a streamlined flat plate parallel to the airflow. The lift coefficient is negligible, ensuring stability in high winds.
  - **Drainage:** A perfectly flat (0-degree) canopy would allow saltwater spray and rain to pool, leading to corrosion and "soiling losses" (dirt/salt blocking the sun). A 2.5-degree slope provides just enough hydraulic head for gravity to clear water from the panels, maintaining high electrical efficiency without compromising safety.[22]
  - **Equatorial Optimization:** Because Indonesia is at the equator, the sun is directly overhead at noon. A flat or near-flat panel actually captures *more* energy over the course of a year than a steeply tilted one, as it captures the sun equally well during both the March and September equinoxes.[23] The "Cosine Loss" of being 2.5 degrees off-perpendicular is statistically insignificant, approximately 0.999, meaning 99.9% of the perpendicular light is captured.

4. Operational Dynamics: The Drift Gill Net Synergy

The viability of solar-electric propulsion is entirely dependent on the vessel's operational profile. For a water taxi that runs continuously at high speed, solar is insufficient. However, for a **drift gill net** fisher, the technology is a perfect fit.

4.1 The Drift Gill Net Cycle

Drift gill netting (*jaring insang hanyut*) is a passive fishing gear. The operational cycle consists of three distinct phases [24]:

1. **Transit (Outbound):** The vessel travels from the port/beach to the fishing ground. This is a high-energy consumption phase.
2. **Setting and Drifting:** The net (often hundreds of meters long) is deployed. The engine is cut. The boat and net drift together with the current. This phase can last 4 to 6 hours.
3. **Hauling and Transit (Inbound):** The net is hauled in (often manually or with a small electric hauler), and the vessel returns to port.

4.2 The "Energy Positive" Fishing Trip

The Gempacs model exploits the "Drifting" phase.

- **The Recharge Window:** While the fisher is drifting, the 2 kWp solar canopy is exposed to the sun. The electric motor is off. The battery is charging.
- **Scenario Modeling:**
  - *Transit Out:* 1 hour @ 3 kW power = 3 kWh consumed.
  - *Drift/Soak:* 4 hours @ Noon. Solar generation = 1.8 kW (avg) x 4 hours = +7.2 kWh generated.
  - *Transit In:* 1 hour @ 3 kW power = 3 kWh consumed.
  - *Net Energy Balance:* $-3 + 7.2 - 3 = +1.2\,\mathrm{kWh}$.
- **Implication:** Under ideal conditions, the fisher returns to port with *more* energy in the battery than they left with. They have effectively refueled for free while working. This is the economic "killer app" of the solar Jukung. Even on cloudy days, the solar contribution significantly extends range and reduces the need for grid charging.[26]

4.3 Reliability and Redundancy

Critics often cite "Range Anxiety" as a barrier. The Gempacs system mitigates this through the solar extender and large battery buffers (10–15 kWh). Furthermore, the exclusion of the unreliable 2-stroke engine actually *increases* technical reliability. Electric motors have one moving part (the rotor). They do not foul spark plugs, clog carburetors, or overheat due to cooling water blockages—common failures that leave fishers stranded at sea.[27]

5. Economic Analysis: The "Swap" Strategy

The economic core of this proposal is the conversion of Operational Expenditure (OPEX) into Capital Expenditure (CAPEX). We model this transformation over a 5-year period using a baseline of **180 fishing days per year**.

5.1 Baseline Economics: The Cost of Combustion

We assume a standard Jukung operator using a 15 hp 2-stroke engine.

- **Fuel Consumption:** 15 liters per trip (conservative average for transit + maneuvering).
- **Fuel Price:**
  - *Official Subsidized Price:* IDR 10,000 / liter (Pertalite).
  - *Real World Cost:* In remote islands or when buying from middlemen, the price is often IDR 12,000–13,000.[7] We will use IDR 11,000 as a weighted average.
- **Oil Cost:** 2-stroke oil adds roughly IDR 2,000 per liter of fuel consumed.
- **Maintenance:** Spark plugs, gear oil, repairs ~IDR 1,500,000/year.
- **Total Annual OPEX:**
  $$(15 \text{ L} \times \text{IDR } 11,000 + \text{Oil}) \times 180 \text{ days} + \text{Maint} \approx \text{IDR } 40,000,000 \text{ (\$2,500)}$$

5.2 Post-Conversion Economics: The Solar Advantage

We assume the fisher converts to the Gempacs system (Cost: ~IDR 100,000,000).

- **Energy Cost:** With the solar canopy providing the bulk of energy, grid charging is minimal. Assuming 20% of energy comes from the grid at non-subsidized rates (IDR 1,444/kWh):
  $$2 \text{ kWh/trip} \times \text{IDR } 1,444 \times 180 \text{ days} \approx \text{IDR } 520,000 \text{ (\$33)}$$
- **Maintenance:** Minimal (bearings check). Estimated IDR 500,000/year.
- **Total Annual OPEX: IDR 1,020,000 ($65)**.
- **Annual Savings: IDR 38,980,000**.

5.3 Financing the Transition: The KUR Framework

The fisher cannot pay IDR 100 million upfront. They need a loan. Under **Regulation of the Coordinating Minister for Economic Affairs Number 1 of 2026**, the KUR (People's Business Credit) framework provides subsidized interest rates for micro-enterprises, specifically tiered for the production sector (fisheries).[28]

- **Loan Amount:** IDR 100,000,000.
- **Interest Rate:** 6% effective per annum (Subsidized by Gov).
- **Tenor:** 5 Years (60 months).
- **Monthly Installment:** Approximately **IDR 1,933,000**.

5.4 The Cash Flow "Surplus"

Let us compare the monthly cash flows:

- **Previous Monthly Fuel Bill:** (IDR 40M / 12) = **IDR 3,333,000**.
- **New Monthly Loan Payment: IDR 1,933,000**.
- **Net Monthly Surplus: + IDR 1,400,000**.

Insight: By switching to electric, the fisher effectively gives themselves a **IDR 1.4 million ($90)** monthly raise *after* paying for the boat. This is transformative for a household living near the poverty line. The "Pak Eko" case study confirms this dynamic, where the elimination of the daily fuel burn doubled his take-home pay and allowed him to send his children to school.[8]

Table 1: Comparative Economic Model (Annual)

Parameter	2-Stroke ICE Jukung	Gempacs Electric Jukung
Energy Source	Subsidized Pertalite	Solar + Grid
Fuel/Energy Cost	IDR 35,000,000	IDR 520,000
Lubrication/Maint	IDR 5,000,000	IDR 500,000
Loan Repayment	IDR 0 (Sunk Asset)	IDR 23,200,000
Total Cash Outflow	**IDR 40,000,000**	**IDR 24,220,000**
Net Savings	-	**+ IDR 15,780,000**
Asset Value (Year 5)	IDR 0 (Scrap)	IDR 40,000,000 (System Life >10 yrs)

6. Financial Engineering: The Guarantee Mechanism

If the economics are so compelling, why hasn't the market solved this? The answer lies in risk perception and structural barriers in the Indonesian banking sector.

6.1 The "Unbankable" Sector and NPL Risks

Commercial banks (BRI, Mandiri, BNI) view the artisanal fishery sector as high-risk.

- **NPL Rates:** The Non-Performing Loan (NPL) rate for the fishery sector reached **5.3%** in late 2023, the highest of all economic sectors.[29] This makes banks extremely reluctant to lend without 100% collateral (e.g., land certificates), which most fishers do not possess.
- **Income Seasonality:** Fishing is weather-dependent. During the monsoon months, income drops to zero. A fixed monthly loan payment structure is incompatible with this variable income stream, leading to technical default.

6.2 The Solution: Sovereign Loan Guarantees

To break this deadlock, the government must intervene not with cash handouts, but with **credit enhancement**.

- **The Mechanism:** The Ministry of Finance reallocates a portion of the *Subsidy Budget* to capitalize a Guarantee Fund managed by **Jamkrindo** or **Askrindo** (State Credit Guarantee Agencies).
- **The Coverage:** The fund provides a guarantee covering 70–80% of the principal risk for loans issued to *Fishery Cooperatives* for electrification projects.[30]
- **The Multiplier Effect:** A guarantee fund is highly capital efficient. IDR 1 Trillion in capital can back IDR 10–15 Trillion in loans (assuming a gearing ratio of 10-15x). In contrast, IDR 1 Trillion in fuel subsidy is consumed and gone in weeks.

6.3 The Role of the Koperasi (Cooperative)

The *Koperasi* acts as the necessary intermediary between the formal banking sector and the informal fisher.[31]

- **Aggregator:** The Koperasi takes the loan on the balance sheet or coordinates the application for 100+ members, reducing administrative costs for the bank.
- **Payment Collection:** The Koperasi manages the Fish Auction Place (TPI). They can implement a "deduction at source" model, where the loan repayment is automatically subtracted from the daily catch proceeds, drastically reducing NPL rates compared to voluntary payments.
- **Asset Management:** The Koperasi can own the batteries as a shared asset, leasing them to members. This reduces the risk for the individual fisher and allows for professional maintenance of the critical components.

6.4 Handling the Weather Risk: The "Climate Grace Period"

To further de-risk the portfolio, the loan product must be structured to accommodate the **180-day fishing baseline**.

- **Grace Periods:** The loan terms should include pre-planned "payment holidays" during the known monsoon months (e.g., January/February in Java Sea).
- **Weather Indexing:** Using BMKG data, if wave heights exceed safe operational limits for extended periods, payments should be automatically deferred. This prevents "Force Majeure" from becoming a "Credit Event".[33]

7. Strategic Implications for Government

This transition aligns with the highest strategic priorities of the Indonesian government: Fiscal Security, Industrial Sovereignty, and the Blue Economy.

7.1 Fiscal De-Risking

Every Jukung converted to electric is one less consumer of subsidized Pertalite.

- **Subsidy Savings:** A single Jukung consumes ~2,700 liters of fuel per year. At a subsidy gap of IDR 3,000–5,000 per liter (difference between market and subsidized price) [34], the government saves **IDR 8-13 million per boat per year** in avoided subsidies.
- **ROI for the State:** If the government provides a guarantee that costs IDR 2-3 million in capital provisioning per boat, the "Fiscal ROI" is achieved in months. Over the 10-year life of the boat, the state saves over IDR 100 million in subsidies—far exceeding the cost of the guarantee.

7.2 Industrial Policy (TKDN)

A national program to electrify 100,000 Jukungs creates a massive, predictable demand for domestic manufacturing.

- **Battery Ecosystem:** This aligns perfectly with Indonesia's ambition to be a global EV battery hub with PT Industri Baterai Indonesia or also known as Indonesia Battery Corporation (IBC), part of the Danantara Indonesia Wealth Fund.
- **Solar Manufacturing:** It creates a domestic market for Indonesian-made solar panels.
- **Shipyards:** It revitalizes local boatyards, tasking them with retrofitting hulls rather than building new wooden boats, creating skilled technical jobs in coastal villages.[14]

7.3 Data Sovereignty and Carbon Monetization

The Gempacs system turns the artisanal fleet into a "Digital Fleet".[35]

- **IUU Fishing:** The IoT GPS tracking allows the KKP (Ministry of Marine Affairs) to monitor fishing effort in real-time, identifying illegal fishing or overfishing in protected zones.
- **Carbon Credits:** The emissions reductions are measurable and verifiable via the IoT data. The government or Koperasi can aggregate these reductions and sell them on the carbon market (Bursa Karbon Indonesia). This revenue stream can be used to further subsidize the interest rates or fund coastal resilience projects.

8. Conclusion

The conversion of maritime fuel subsidies into loan guarantees represents a rare "Pareto Optimal" policy intervention: every stakeholder benefits.

- **The Fisher** gains a modern asset, doubles their disposable income, and breaks free from the volatility of fuel prices.
- **The State** reduces its chronic fiscal deficit, lowers its carbon footprint, and stimulates a high-tech domestic industry.
- **The Environment** is spared the acoustic trauma and chemical pollution of millions of liters of unburned fuel.

By leveraging the technical specificity of the **Gempacs model** (2 kWp/2.5-degree slope) and the financial resilience of the **Koperasi**, Indonesia can transform the "Sunk Cost" of subsidies into the "Sovereign Capital" of a sustainable Blue Economy. The technology is ready; the economics are sound. All that is required is the political will to re-engineer the flow of capital from consumption to investment.

9. Appendix: Technical Data

3.2 The Solar Canopy: Physics and Geometry

The defining feature of the Gempacs model is the **2 kWp Solar Canopy**. The integration of such a large array on a small boat is made possible only by the Jukung's outriggers, but it introduces significant engineering challenges regarding aerodynamics and stability.

3.2.1 The 2 kWp Sizing Rationale

Why 2 kWp?

- **Energy Density:** Indonesia lies on the equator. The average solar irradiance (Global Horizontal Irradiance - GHI) is approximately 4.8 kWh/m²/day.[17]
- **Yield Calculation:** A 2 kWp array (approx. 10 m²) operating at a conservative system efficiency of 75% (accounting for heat, cabling, and minor shading) will generate:

$$E_{daily} = 2\,\mathrm{kWp} \times 4.8\,\mathrm{PSH\ (Peak\ Sun\ Hours)} \times 0.75 \approx 7.2\,\mathrm{kWh/day}$$

- **Operational Relevance:** 7.2 kWh is enough energy to drive a 10 kW motor at "cruise" power (approx. 3 kW) for nearly 2.5 hours. For a drift gill net fisher who spends hours drifting (charging), this effectively extends the range to infinity during daylight hours.

3.2.2 The 2.5-Degree Slope: An Aerodynamic Compromise

Gempacs specifies a canopy slope of exactly **2.5 degrees**. This is not an arbitrary figure; it is a calculated optimization for the maritime environment.

- **The Lift Problem (The "Wing" Effect):** A flat plate (the solar canopy) moving through the air behaves like an airfoil. If the canopy were tilted at 15–20 degrees to optimize solar intake, a headwind or a sudden gust from a squall would generate massive aerodynamic lift (L).

$$L = \frac{1}{2}\rho v^2 A C_L$$

  Where ρ is air density, v is wind speed, A is area (10 m²), and C_L is the coefficient of lift. At high angles of attack, C_L increases dramatically.[19] A strong gust could flip a lightweight Jukung.
- **The Drag Problem:** A steep canopy also increases frontal area, creating parasitic drag that the electric motor must overcome, draining the battery and reducing range.[21]
- **The 2.5-Degree Solution:**
  - **Minimal Lift/Drag:** At 2.5 degrees, the canopy is effectively a streamlined flat plate parallel to the airflow. The lift coefficient is negligible, ensuring stability in high winds.
  - **Drainage:** A perfectly flat (0-degree) canopy would allow saltwater spray and rain to pool, leading to corrosion and "soiling losses" (dirt/salt blocking the sun). A 2.5-degree slope provides just enough hydraulic head for gravity to clear water from the panels, maintaining high electrical efficiency without compromising safety.[22]
  - **Equatorial Optimization:** Because Indonesia is at the equator, the sun is directly overhead at noon. A flat or near-flat panel actually captures *more* energy over the course of a year than a steeply tilted one, as it captures the sun equally well during both the March and September equinoxes.[23] The "Cosine Loss" of being 2.5 degrees off-perpendicular is statistically insignificant ($ \cos(2.5^{\circ}) \approx 0.999 $), meaning 99.9% of the perpendicular light is captured.

Table 2: Aerodynamic Forces on 2 kWp Canopy (10 m²)

Wind Speed (Knots)	Angle of Attack (α)	Lift Force (N)	Drag Force (N)	Risk Assessment
20 kts (10 m/s)	**2.5°**	**~50 N**	**~20 N**	**Safe**
20 kts (10 m/s)	15.0°	~600 N	~180 N	Risk of Bow Lift
40 kts (Squall)	**2.5°**	**~200 N**	**~80 N**	**Manageable**
40 kts (Squall)	15.0°	~2,400 N	~700 N	**Critical Failure**

Note: Calculations based on standard flat plate aerodynamic coefficients

Table 3: Gempacs System Bill of Materials (Estimated)

Component	Specification	Estimated Cost (IDR)
Electric Motor	10-15 kW BLDC Outboard	35,000,000
Battery Bank	10-15 kWh LiFePO4 (48V/72V)	45,000,000
Solar Array	2 kWp Monocrystalline Flexible/Rigid	10,000,000
Controller & IoT	MPPT + VCU + GPS/4G	5,000,000
Structure/Install	Aluminum/Bamboo Frame + Labor	5,000,000
TOTAL		**100,000,000**

Source: Market estimates derived from.[27]

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