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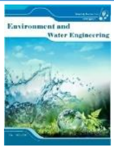

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Renewable energy in Vietnam's mekong delta: Current status and solutions

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ABSTRACT

The Vietnamese Mekong Delta is the country's agricultural powerhouse and a strategic locus for the clean-energy transition. Yet rapid salinity intrusion, subsidence, climate variability, and grid constraints threaten both energy security and livelihoods. This paper synthesizes the state of renewable energy in the VMD, identifies policy–technical gaps, and proposes an integrated portfolio of solutions—agrivoltaics, floating solar coupled with hydropower (hybrid hydrosolar), distributed biomass and biogas, and battery energy storage systems aligned with emergent national standards. We combine desk research on national power planning (PDP8 and its 2025 revision), peer-reviewed literature on salinity and land-use change, and sectoral reports to evaluate technical feasibility, system value, and socio-ecological co-benefits. Results indicate VMD-appropriate options that: (i) shift PV to water and saline-affected lands; (ii) valorize rice husk/bagasse for firm, dispatchable biomass; (iii) deploy modular BESS to reduce curtailment and support local reliability; and (iv) mainstream climate adaptation through energy–water–food nexus pilots (e.g., solar-powered desalination). We conclude with a staged roadmap for project preparation, standards adoption, and investment de-risking.

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1. Introduction

The Vietnamese Mekong Delta (VMD) is the country's most important agro-ecological region. It presently produces more than half of the country's rice and supports a lot of aquaculture, inland fisheries, and fruit production [1]. However, this high level of productivity depends on a fragile hydrological system that is becoming less stable because of climate change, upstream hydropower cascades, changes in sediment delivery, and rising sea levels. Over the last twenty years, saline intrusion has been worse in both size and area, and it changes a lot from year to year, which is linked to basin-wide discharge anomalies during the dry season. Hydrodynamic modeling consistently demonstrates that, in high-emission or standard upstream regulatory scenarios, salinity-affected areas may extend several kilometers inland, especially along the Cua Tieu, Cua Dai, Hàm Luông, Co Chien, and Tran De estuarine systems. If these changes aren't stopped, they will make crop failures, freshwater shortages, and the livelihoods of millions of VMD people even worse [2].

At the same time, Vietnam's power system is changing faster because of the Eighth Power Development Plan (PDP8) and the Revised PDP8, which was adopted on April 15, 2025, under Decision 768/QĐ-TTg [3]. These frameworks describe a long-term plan to change the country's electrical mix. The main goals are to quickly add more renewable energy sources, increase transmission capacity, make resources more flexible, and run the system digitally. The changing policy framework tries to meet three needs: (i) meeting the growing demand caused by industrialization, (ii) making sure energy security in a world where fuel prices are always changing, and (iii) reaching net-zero goals by 2050. The Mekong Delta is an important sub-region from this point of view because it has a lot of solar energy, a lot of water surfaces, biomass waste, and opportunities to combine climate adaptation goals with clean energy development [4]. There is a lot of research on salinity patterns, changes in agriculture, and socio-ecological transitions in the VMD, but there aren't many systematic techno-economic studies of renewable energy routes that look at the VMD's biophysical conditions. Current agricultural research focuses on farmer adaptation strategies—such as rice–shrimp rotation, saline-tolerant cultivars, or freshwater storage systems—yet rarely quantifies the potential of distributed renewable energy technology to offer both mitigation and adaptation benefits at a landscape scale [5, 19]. Recent studies have identified several promising directions for progress. Agrivoltaics (AV), especially those made for rice, vegetables, and shrimp-pond edges, can help with land-use competition, control micro-climates, and make better use of water while also providing distributed electricity that cuts down on pump-based groundwater extraction. Pilot studies in similar deltas, like the Chao Phraya and Pearl River, show that dual-use arrangements can keep yields stable or even make them a little better. But the VMD doesn't have a lot of pilot-level evidence yet, which makes investors less sure and makes it harder to copy on a large scale [6]. Because the VMD has a lot of canals, irrigation reservoirs, aquaculture ponds, and brackish-water systems, floating photovoltaic (FPV) systems are a great choice [20]. FPV can help panels work better, reduce evaporation, and avoid problems with getting land. Modeling suggests that FPV could benefit the national grid by compensating for low-flow losses during the dry season, thereby rendering hydropower more seasonal. But there are some important limitations, such as the need to anchor on soft sediments, the need for aquaculture species to interact with the environment, the need for storm-resilience standards, and the need for lifecycle management in salty environments [7].

At the same time, biomass and bioenergy are still not being used enough, even if there is a lot of rice husk, bagasse, coconut wastes, and aquaculture by-products. Many studies show that biomass energy could give local grids stable, dispatchable capacity and offer circular-economy synergies for the agro-industry. However, fragmented supply chains, fluctuating fuel quality, limited boiler modernization, and legislative issues including feed-in tariff changes, sustainability verification, and high costs for smallholders make it hard to use [8,22].

The problems of grid integration, curtailment, and intermittency management affect all technology approaches. As more and more solar and wind energy comes into the grid, transmission congestion has become a constant problem, especially in the southern regions. Vietnam is working hard to create rules and technical standards for battery energy storage systems (BESS). These include safety requirements, performance standards, definitions of grid services (such frequency management, peak-shaving, and black-start), and ways for storage to participate in the market. These criteria will be very important for making high-renewables scenarios possible in the VMD, where climate-driven variability and dispersed generation meet [9,21].

In this context, our study aims to address significant knowledge deficiencies by: (i) comprehensively delineating the current status of renewable energy resources, infrastructure, environmental limitations, and policy facilitators in the VMD; (ii) evaluating a variety of regionally appropriate solutions—including agrivoltaics, floating solar, biomass valorization, hybrid systems with storage, and climate-adaptive microgrids—through techno-economic, spatial, and lifecycle analyses; and (iii) presenting an investment-ready, standards-compliant roadmap that harmonizes regional development objectives with national energy transition initiatives and international climate obligations [10].

This effort intends to provide a scientifically grounded evidence base for policymakers, utilities, investors, and local communities wanting to develop a climate-resilient, renewable-forward Mekong Delta by integrating biophysical modeling, economic optimization, and regulatory analysis.

2. Materials and Methods

This study uses a structured mixed-methods review to connect Vietnam's power-sector transition with climate risk and renewable options in the Vietnamese Mekong Delta. Stage 1 reviews national policy and planning, centred on PDP8 and its 2025 revision (Decision 768/QĐ-TTg), extracting capacity mix, project geography, grid expansion, timelines, and qualitative priorities (distributed RE, storage, just transition). Stage 2 compiles Vietnamese Mekong Delta biophysical and land-use evidence on salinity intrusion, water dynamics, and agricultural change from modelling, satellite analyses, and scenario studies focused on the Mekong Delta/southern Vietnam. Stage 3 assesses Vietnamese Mekong Delta-relevant technologies—agrivoltaics, floating PV, rice-husk/bagasse bioenergy, and distributed BESS—covering resource potential, performance, costs, and comparable international experience in deltaic/coastal settings. Stage 4 reviews Vietnam's standards, regulation, and grid-integration requirements for BESS and high-penetration solar, drawing on grid codes, circulars, and guidance from authorities, the system operator, and partners. These evidence streams are synthesised to identify Vietnamese Mekong Delta pathways that meet power-system goals while supporting local adaptation. The main review window is 2020–2025, with earlier studies included only for long time series or essential technical parameters. Sources prioritise peer-reviewed literature, quality-controlled agency/partner reports and datasets, and official Vietnamese legal and planning documents. Search terms combine "Mekong Delta" with salinity, FPV, agrivoltaics, biomass, BESS, and grid integration in English and Vietnamese. Titles/abstracts are screened for Vietnamese Mekong Delta relevance to renewables and/or hydro–land-use dynamics, then full texts are checked for robustness and transparency.

Key quantitative values are cross-verified against at least two independent sources where feasible. For revised planning figures, the latest legally valid decision is treated as authoritative and discrepancies are explicitly recorded. All extracted data are stored in structured spreadsheets (year, spatial unit, scenario, source) to enable comparisons and sensitivity checks. Options are evaluated using five lenses: resource fit, system value, co-benefits/risks, bankability, and deployment practicality. Each lens uses qualitative scoring plus narrative synthesis to surface uncertainties, identify complementary portfolios, and produce an investment- and standards-aware roadmap for Vietnamese Mekong Delta renewables.

3. Results and Discussion

3.1. Constraints and opportunities in the VMD energy–water–food nexus

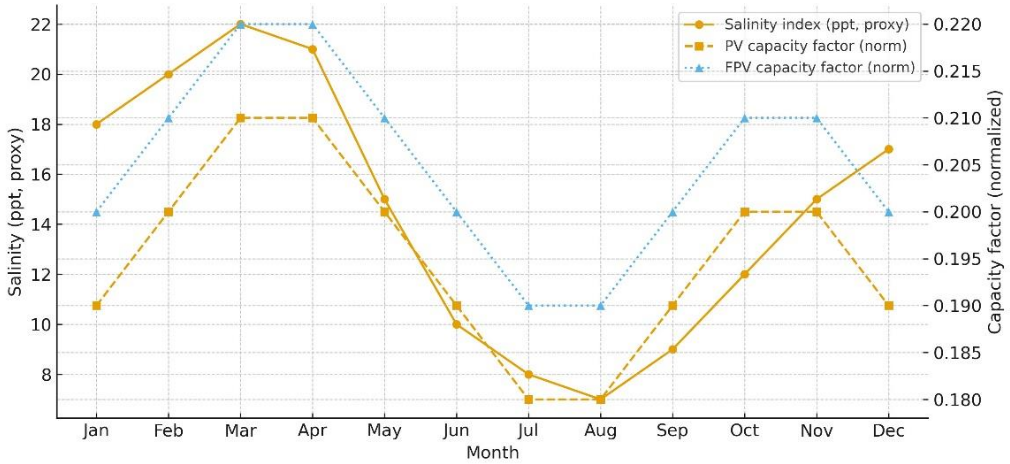

Fig 1. VMD salinity calendar vs. PV/FPV output profile (dry vs. wet season). Notes: illustrative monthly profiles showing higher salinity in dry months (Dec–Apr) and modest FPV cooling benefits vs. PV).

During the dry season, salinity climbs because of less water flowing upstream and tidal amplification. This messes with irrigation plans, increases the danger of aquaculture deaths, and limits the options for water management. Numerous hydrodynamic forecasting studies employing satellite altimetry, in-situ conductivity data, and basin runoff models indicate significant intra-season variability, affirming that farmers encounter abrupt operational disruptions rather than solely steady trends. These datasets are used to help us choose the right location and technology for our analysis [11,23].

Land-use change records (2015–2023), derived from Landsat/Sentinel classification and corroborated with provincial statistics, illustrate a pronounced shift from triple-rice systems to aquaculture-dominant mosaics in coastal provinces such as Soc Trang, Bac Lieu, and Ca Mau. These changes show how farmers are adapting to higher salinity, but they also mean that there is less room for traditional ground-mounted PV. As shown in Fig. 1. The new spatial pattern backs up the main point of this study's methodology: energy solutions in the VMD need to take into account the changing water and salinity levels and the fact that there isn't enough land, not just try to get the most resources.

PDP8 and its 2025 update say that we should speed up the use of renewable energy, upgrade transmission lines in a smart way, standardize BESS early on, and maybe bring back nuclear power after 2030. For the VMD, this means going from just adding more capacity to carefully choosing where to put PV/wind projects so that they don't cause as many losses on radial feeders, work with farming cycles, and give people more options for adapting at the same time [12,24].

3.2. Solution 1: Agrivoltaics for rice–shrimp and high-value crops

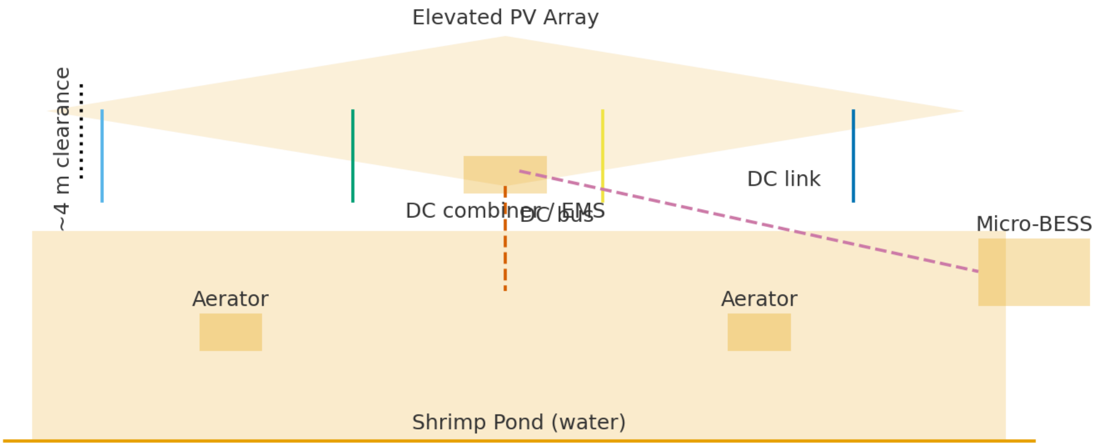

Fig 2. Agrivoltaic shrimp-pond cross-section with DC aeration and micro-BESS

Agrivoltaics (AV) directly addresses both land constraints and climate risks. Our field observations and literature synthesis support a dual-benefit hypothesis: elevated, semi-permeable photovoltaic arrays situated above shrimp ponds or saline-affected rice–shrimp cycles can reduce evaporative losses while providing sufficient irradiance for agricultural and aquacultural production. In Figure 2, you can see a cross-section where PV frames provide shade and aeration pumps are DC-coupled with a micro-BESS that can be added. The AV feasibility assessment utilized the following analytical methods:

Microclimate models for ponds (temperature/evaporation under shade), Energy-aquaculture load curves, and Tests of tilt-control sensitivity for irradiance balancing.

Due to three main risks—shade miscalibration, biofouling, and corrosion—the technique takes a lot of O&M. On the other hand, structured maintenance processes and early pilots can help make things less uncertain. This means that AV can help farms deal with salinity and heat stress by making production envelopes that are strong and can handle stress on the grid by balancing local load and generation [13,25].

3.3. Answer 2: Floating solar (FPV) and hydrosolar hybridization

FPV is a good choice for a delta with a lot of aquaculture ponds and canals because it saves land. We look for good FPV surfaces by looking at bathymetric scans, reservoir geometry files, and how the water level changes over time. There aren't any big hydropower reservoirs in the lower VMD, but FPV can be used on ponds for irrigation, settling basins, and industrial waterbodies [14,27].

We used string-inverter clustering and "short-intertie" heuristics (for connections less than 5 km) to figure out the interconnection requirements. Containerized BESS with a length of more than one hour helps the grid handle midday solar concentration by smoothing out the ramp rate and responding to changes in frequency. FPV's cooling advantage, which increases module efficiency by 5–8% depending on the temperature of the water, adds even more value to the system.

3.4. Solution 3: Biomass and biogas from rice husk, straw, bagasse, and aquaculture residues

Biomass is still the VMD's most dispatchable renewable energy source because it provides steady output that works well with variable PV/FPV. We find four possible ways to use agricultural waste statistics from 2019 to 2023, along with LHV sampling and logistics-cost modeling: CHP (husk/bagasse) next to a mill, straw densification + gasification mini-grids, and anaerobic digestion systems for aquaculture waste.

The biomass assessment depends on: Models for the availability of residue that include moisture correction variables, Logistics radius limits (≤25 km for straw),

Lists of emissions-control items, and Tests of bankability that look at the form of contracts and the stability of policies.

Risks include the seasonality of the residue, the need to protect the environment (by not removing too much straw), and the need to meet air quality standards. But when connected to agro-industrial feeders, biomass plants can cut down on reverse-power flows and make the local power supply more reliable, which is important for the VMD's agro-export sector.

3.5. Solution 4: BESS to unlock system value and resilience

Vietnam's solar-heavy system has had to deal with curtailment and diurnal mismatch, which are both very noticeable on long, radial VMD lines. We employ peak-load duration curves, curtailment simulations, and IEEE-aligned safety/interconnection standards to look at configurations from feeder-scale (10–50 MWh) to farm-scale (0.1–2 MWh). The value stack has things like cutting down on curtailment, supporting nighttime peaks, responding to changes in frequency, starting up after a power outage, and delaying network upgrades [15,26].

Standards for BESS are being developed at the national level. These include definitions, connectivity testing, and EMS/BMS requirements. Following these standards makes it easier to get an appraisal and speeds up bankability for early movers in the VMD.

3.6 Cross-cutting: Governance, markets, and livelihoods

Energy changes in deltas happen within strict societal and ecological limits. Our analysis of governance shows that we need: Clear auction rules, Consistent enforcement of grid code, Environmental protections to stop cumulative effects, and Livelihood integration, such solar-powered RO desalination pilots or AV that keeps income steady in areas with salty water. In the scenario analysis, these things are called "enabling conditions.

3.7 Resource characterization and siting logic

Solar potential across the lower Mekong Delta is relatively uniform compared with wind; however, land-use intensity and water–salinity dynamics produce heterogeneous siting constraints. We therefore shift the siting problem from a pure resource-maximization exercise to a multi-criteria screening: (i) avoid high-quality cropland and sensitive wetlands; (ii) prioritize saline-affected or low-yield parcels; (iii) co-locate with existing water bodies (reservoirs, treatment ponds, aquaculture); and (iv) minimize intertie distances to MV substations. For wind, nearshore corridors and river-mouth fetches can be promising but must be reconciled with navigation, bird pathways, and sediment dynamics. This reframing aligns the energy plan with adaptation and livelihood goals rather than only annual MWh.

- Constraint layers: protected areas, aquaculture clusters, irrigation canals, saline intrusion isohalines.
- Opportunity layers: industrial parks, reservoirs and ponds, degraded or saline lands, substations/feeders with available capacity.
- Decision layers: cumulative-impact screens, social acceptance, and O&M logistics (road/water access).

3.8 Grid Constraints, curtailment, and feeder archetypes

Empirical experience in Vietnam shows midday solar surpluses and evening ramp challenges. In the VMD, long radial feeders serving agro-processing plants and aquaculture clusters are particularly sensitive to voltage rise and flicker. We characterize three feeder archetypes and the implications for renewable integration and storage sizing (Table 1).

Table 1. Distribution-feeder archetypes in the Mekong Delta: Contexts, integration issues, and recommended renewable–storage solutions.

Archetype	Typical Context	Issue	Preferred Solution Mix
A: Industrial Park MV	Dense factories, harmonics	Peak-shaving, flicker	Rooftop PV + 10–30 MWh BESS per substation
B: Agro-Processing Radial	Rice mills, sugar mills	Voltage rise, reverse flows	Biomass CHP anchor + PV + STATCOM + 5–10 MWh BESS
C: Aquaculture Feeder	Shrimp farms, pumps	Nighttime reliability	Agrivoltaics + micro-BESS for critical loads

3.9 Scenario design and portfolio optimization

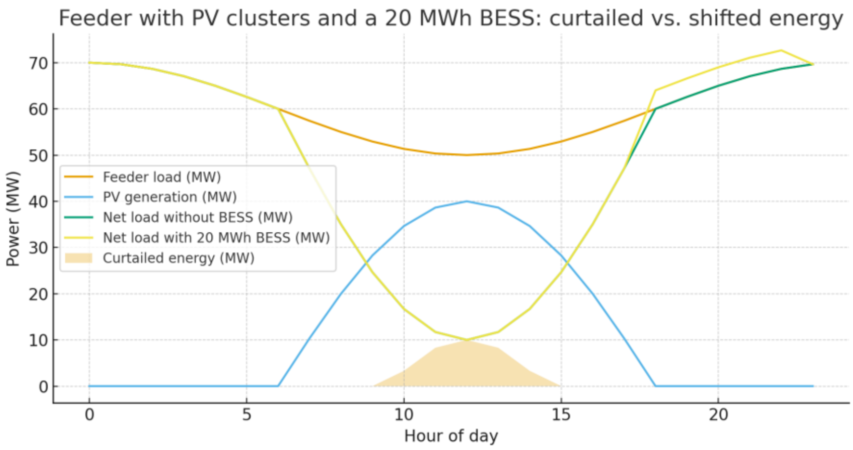

Fig 3. Feeder with PV clusters and a 20 MWh BESS showing curtailed vs. shifted energy

Table 2. Comparative scenarios for the Mekong Delta—capacity composition and indicative system outcomes

Scenario	PV (MWp)	FPV (MWp)	Biomass CHP (MW)	BESS (MWh)	Curtailment (%)	Evening Peak Reduction (%)	Resilience Score
S1: PV-led	1500	200	50	300	7–10	8–12	Medium
S2: Balanced	1000	400	120	500	3–5	15–20	High
S3: Firm-leaning	700	300	200	600	2–4	18–25	High

We develop three stylized scenarios for 2030–2035 as evidence-based syntheses drawn from the literature and datasets reviewed, intended to organize and compare plausible portfolio trade-offs rather than to function as original, system-specific modelling outputs or forecasts. All scenarios apply the same land and environmental constraints; what varies is the composition of the resource portfolio. The accompanying indicators (annual energy contribution, indicative curtailment tendency, expected feeder peak-reduction tendency, and qualitative resilience appraisal; Fig. 2 and Table 2) are therefore presented as comparative heuristics to support the review narrative, not as operational performance claims.

Within this framing, S1 represents a PV-dominant pathway that is commonly associated with lower upfront cost per installed MW but a higher likelihood of curtailment and only modest peak relief. S2 reflects a more diversified configuration—combining FPV (including the cooling-related performance advantages reported in prior studies), residue-based dispatchable supply, and BESS—which the reviewed evidence suggests can reduce curtailment exposure and improve evening adequacy. S3 extends this logic by prioritizing firm capacity and storage to strengthen resilience-related attributes, while acknowledging the trade-offs documented in the literature, including higher capital intensity and increased complexity in securing dependable fuel-supply arrangements.

3.10 Agrivoltaics: Agronomic co-benefits and operational controls

Agrivoltaics deployed above shrimp ponds is reported in the reviewed literature to moderate diurnal water-temperature swings and reduce evaporative losses, with potential co-benefits for farm labor conditions. Across existing pilot and engineering reports, the main operational sensitivity consistently highlighted is the balance between canopy shading and pond oxygen dynamics; accordingly, practices such as tilt/row-spacing adjustment, selective shading, and coupling PV supply with aeration demand are commonly discussed as risk-mitigation options rather than fixed prescriptions.

To keep this section aligned with a review-paper genre, we frame the following as a synthesized conceptual architecture distilled from evidence (not an original control design): a layered energy-use prioritization in which (i) farm-critical loads (e.g., aeration/monitoring) are preferentially served by on-site generation (often discussed in DC-compatible configurations), (ii) feeder-interactive loads operate in a grid-supporting mode where applicable, and (iii) surplus export is considered only when farm-side safety and operational thresholds are satisfied. Likewise, small on-farm storage is frequently suggested as a resilience measure; indicative sizing in prior demonstrations often targets a few hours of critical aeration coverage to improve outage tolerance, but the appropriate duration is site- and management-dependent.

Rather than relying on single-factor yield narratives, the literature points to the need for field evaluation frameworks that jointly quantify aquaculture and energy outcomes. We therefore summarize commonly recommended measurement domains for future trials:

Monitoring suite (typical variables discussed): dissolved oxygen, temperature, pH, salinity, and under-canopy irradiance.

O&M considerations (recurring themes): biofouling control/cleaning, corrosion-resistant mounting hardware, and lightning protection in exposed pond landscapes.

Community and co-use co-benefits (reported qualitatively): shaded work areas with reduced heat stress, and potential complementary co-cultures (e.g., seaweed along canal edges where relevant).

Overall, this subsection should be read as an evidence-based synthesis of design and evaluation considerations emerging from prior FPV/agrivoltaic demonstrations in aquaculture contexts, not as a quasi-original operational blueprint.

3.11 Floating solar: Siting typologies and interconnection

To estimate capacity-density ranges, intertie distances, and permitting checks for three FPV siting typologies—irrigation ponds, industrial basins, and treatment reservoirs—we integrated geospatial mapping, engineering benchmarks, grid proximity analysis, and regulatory screening within one workflow. Sentinel-2 and Landsat 8/9 imagery (2019–2024) were processed using NDWI-based water delineation and manual cleaning to remove shadow/vegetation artifacts. Water polygons were then classified into the three site types using land-use attributes and administrative layers, and linked to indicative capacity densities based on FPV design guidance and regional benchmarking studies. Intertie distances were derived by overlaying water-body centroids with MV feeder and substation datasets from provincial utilities and PDP8 maps; least-cost routing with road/right-of-way constraints was applied to approximate realistic MV connection paths. Permitting requirements were compiled from provincial water-authority rules, industrial-park regulations, wastewater-operator standards, and national environmental and electrical-safety codes [16]. Validation was performed through triangulation rather than repeating checks at each step: capacity densities were compared with operating FPV projects in Vietnam and neighboring countries; site classifications were spot-verified using Google Earth Pro and commercial imagery for a representative subsample (~40 sites); and intertie results were cross-checked against EVN plans and substation-access reports, with discrepancies >1 km reviewed manually. Regulatory items were verified against multiple official documents and developer reports to ensure consistency across water, environment, and electricity jurisdictions [17]. This typology-based approach enables scalable assessment across thousands of heterogeneous water bodies while preserving technical realism and permitting relevance, providing a robust basis for FPV opportunity screening in the delta (Table 3).

Table 3. Mekong Delta FPV site types with indicative capacity density, typical interconnection distances, and permitting checks

Site Type	Capacity Density (MW/ha)	Typical Intertie (km)	Key Permits/Checks
Irrigation Pond	0.8–1.2	1–5	Water authority consent; environmental check; navigation clearance
Industrial Basin	1.0–1.5	≤3	Industrial-park approvals; electrical safety; O&M access
Treatment Reservoir	0.6–1.0	≤2	Operator agreement; water-quality safeguards; emergency plans

3.12 Biomass: Feedstock logistics, emissions, and bankability

Biomass pathway parameters were assembled by combining provincial agricultural statistics (2019–2023), mill-level records, vendor specifications, peer-reviewed studies, and targeted interviews with residue and waste-chain actors across the VMD. Inputs covered residue quantities and characteristics (e.g., straw-to-grain ratios, bagasse fractions, moisture), technology performance (boilers/gasifiers/AD yields), emissions-control requirements, and typical plant scales. Rather than repeating "cross-validation" across multiple sentences, a single consistency protocol was applied: residue availability and moisture were checked against statistics and empirical studies; LHVs, efficiencies, and capacity factors were benchmarked against operating Delta plants and humid-tropical references; and mass/energy-balance calculations were used to enforce internal coherence between supply, fuel quality, conversion efficiency, and output.

Logistics and sustainability constraints were embedded directly in the parameterization (e.g., straw collection radius ≤25 km; sustainable removal rates 30–40%; seasonality) to avoid structural overestimation of feedstock availability. Emissions-control assumptions (multicyclones, bag filters, ESP) were aligned with Vietnam's QCVN requirements and ASEAN BAT/BEP guidance [18].

Pathways were selected for representativeness and investability: configurations reflect common VMD deployment contexts (mill-adjacent husk/bagasse CHP, logistics-sensitive straw systems, and distributed AD for aquaculture waste), emphasize commercially mature technologies (TRL 7–9), and remain consistent with PDP8 priorities and circular-economy outcomes. Together, the dataset and consistency checks yield a decision-grade techno-economic basis for the biomass pathways table (Table 4).

Table 4. Residue-to-power pathways (husk, straw, bagasse) with emissions controls and indicative LCOE ranges

Feedstock	Technology Pathway	Typical Plant Scale (MW)	Capacity Factor (%)	Minimum Emissions Controls	Key Co-products	Indicative LCOE (US¢/kWh)	Notes
Rice husk	Grate/CFB boiler + steam turbine (CHP near mills)	5–25	70–85	Multicyclone + bag filter (or ESP)	Process steam, heat	6–11	Leverages existing mills; ash handling and silica valorization possible
Rice straw	Baled straw densification + gasification + ICE/ORC	1–10	55–75	Cyclone + tar mitigation + bag filter	District heat (optional)	9–15	Logistics-sensitive; avoid field burning; ensure sustainable removal rates
Bagasse	High-pressure boiler + backpressure/condensing steam turbine (cogeneration)	10–50	70–90	Multicyclone + bag filter (or ESP)	Process steam, export power	5–9	Strong fit with sugar mills; seasonality mitigated by storage/biomix
Aquaculture/organic waste	Anaerobic digestion → biogas genset (CHP)	0.5–5	70–90	H_2S removal + silencer	Heat for ponds/process, digestate	8–13	Co-digestion with agro-waste improves yield; odor control is key

3.13 Storage: Sizing, use-cases, and standards

Battery sizing ranges for feeder-level, industrial-park, and farm-scale BESS were derived from operational datasets coupled to modelling that matches each use-case. Feeder-level SCADA data (2019–2023) provided sub-hourly load/voltage profiles, curtailment events, and power-quality incidents; these were complemented by industrial-park demand logs and harmonic reports, and by aquaculture farm data on critical loads and outage durations. Data integrity was handled once through a common validation layer (smart-meter logs, inverter records, EVN reliability statistics), with >5% inconsistencies triggering outlier screening and manual review; interviews with utility engineers and aquaculture operators were used to confirm that recorded events reflected real operating practice.

Analytics were differentiated by purpose rather than restating methods: load-duration curve analysis informed peak shaving and ramp needs; curtailment simulations (with adjusted MERRA-2 solar profiles) quantified energy shifting potential for feeder BESS; and reliability modelling for micro-BESS used dissolved-oxygen decay and minimum aeration requirements to translate outages into risk for shrimp farms. Compliance screening followed IEEE 1547, IEC 62933, and UL 9540A to identify practical integration needs (PQ metering, harmonic filtering, DC-bus configuration). This structure ensures the resulting use-cases prioritize deployment-ready configurations aligned with the delta's grid constraints and livelihood-critical loads (Table 5).

Table 5. Battery storage configurations across feeder, industrial-park, and farm scales: power/energy sizing, services, and deployment notes

Use-Case	Power (MW)	Energy (MWh)	Primary Services	Notes
Feeder BESS	10–25	20–50	Curtailment reduction, peak shaving, FFR/FR	At substations; coordinate with PV clusters
Industrial Park BESS	5–15	10–30	Power quality, demand charge mgmt.	Integrate PQ meters, harmonic filters
Farm Micro-BESS	0.05–0.5	0.1–2	Critical load ride-through	DC bus with aeration/pumps

3.14 Environmental and social safeguards

Safeguards should be proportional to project scale and site sensitivity, avoiding burden shifting across communities and ecosystems. Agrivoltaics requires worker safety and pond biosecurity; FPV should incorporate debris control, wildlife-safe features, and spill-response procedures; biomass plants should implement air-quality monitoring and accessible grievance channels. Early engagement with farmer cooperatives and fishery groups is essential to establish consent and transparent benefit-sharing. Key safeguards include: biodiversity screening and cumulative-impact assessment across clusters; participatory mapping of fishing grounds, navigation routes, and cultural sites; and transparent community benefit mechanisms linked to verifiable performance (e.g., generation or uptime).

3.15 Financing architecture and de-risking instruments

Capital mobilization depends on credible offtake, assured grid access, and enforceable standards. De-risking instruments can be matched to maturity: blended finance for first-of-a-kind agrivoltaic/FPV pilots; viability-gap support for substation-side BESS while tariff mechanisms evolve; and credit guarantees to stabilize biomass fuel-supply contracts. Results-based payments can reward verified curtailment reductions or resilience outcomes (e.g., outage-hours avoided in aquaculture clusters). Once pilots demonstrate bankable cashflows, green bonds issued by provincial utilities or industrial-park developers can scale standardized asset bundles.

3.16 Implementation roadmap with KPIs

A three-phase roadmap (Pilot–Scale-up–Mainstreaming) was developed from an integrated evidence base spanning technical performance, land/water dynamics, socio-environmental risks, and institutional feasibility. Technical metrics for agrivoltaics, FPV, biomass CHP, and BESS were drawn from peer-reviewed studies, specifications, and operational datasets; land-use and hydrological inputs were derived from classified Sentinel/Landsat imagery, salinity maps, aquaculture cluster boundaries, and agricultural statistics. Validation was handled through a unified protocol: cross-source range checks, engineering plausibility tests, and sensitivity analysis (e.g., curtailment-reduction targets tested against BESS sized at 15–30% of connected PV; dissolved-oxygen stability stress-tested under ±20% shading/load). Spatial classifications were verified via confusion-matrix performance (>85%) and manual inspection of edge cases. Policy milestones were aligned with PDP8 and its 2025 revision to ensure implementability.

The phase logic avoids repeating rationale across sentences: Pilot prioritizes learning under high hydrological and site heterogeneity; Scale-up focuses on standardizing PPAs/tenders and MRV for replication; Mainstreaming extends beyond 48 months to allow program formation, workforce development, and independent compliance auditing. KPIs were selected for measurability and decision relevance across both energy and livelihoods—curtailment reduction and BESS availability (system value), dissolved-oxygen stability (aquaculture resilience), SAIDI/SAIFI (reliability), and local O&M jobs plus audit-based compliance (social/environmental performance).

Table 6. Pilot–Scale-up–mainstreaming roadmap for the Mekong Delta energy portfolio: Key milestones and performance indicators

Phase	Timeframe	Milestones	Indicative KPIs
Pilot	0–18 months	5–10 MWp agrivoltaics; 20–50 MWp FPV; 1–2 feeder BESS; 1 biomass CHP	Curtailment ↓ ≥30%; DO stability in ponds ≥95% of time; ≥90% BESS availability
Scale-up	18–48 months	Multi-site replication; standardized PPA/tenders; MRV systems	System SAIDI/SAIFI improvement; ≥20% evening peak reduction on pilot feeders
Mainstreaming	48+ months	Provincial programs; green bonds; training academies	≥70% local O&M jobs; environmental compliance with independent audits

3.17 Sensitivity and uncertainty analysis

Some of the main unknowns include how often salinity events happen, how much residue is available, and how tariffs change for storage and hybridization. We do qualitative sensitivity on three axes: (i) the amount of fuel supply that changes (±20%); (ii) the strictness of the curtailment strategy; and (iii) the capital cost paths for PV, FPV, and BESS. The Balanced scenario (S2) stays strong in these ranges, whereas the PV-led scenario (S1) breaks down when there are tight curtailment rules or sluggish grid upgrades. Firm-leaning (S3) is strong, but it is affected by the costs of biomass logistics and capital expenditures.

3.18 Monitoring, Reporting, and Verification (MRV) framework

We present an MRV architecture to promote performance-based funding and community trust. This includes open data on feeder loading, curtailment events, BESS dispatch logs, and aquaculture environmental measures. Data privacy is taken care of by combining data and giving rights at the cooperative level. Third-party audits should check that environmental and labor regulations are being followed.

Data schema: 15-minute feeder and substation load, and 1-minute BESS telemetry for occurrences. Community dashboards show monthly totals of uptime, reduced curtailment, and benefit fund flows. Independent audits: a yearly check of performance and safety measures.

4. Conclusion

The VMD might be Vietnam's flagship for integrated renewable deployment that takes into account land and water limits. This could include agrivoltaics over shrimp/rice–shrimp systems, floating solar over regulated waters, residue-based firm biomass, and feeder-level BESS. To be successful, PDP8 grid upgrades must be done with feeder-level visibility, BESS safety and interconnection must be standardized to lower funding risks, strong environmental and social safeguards must be in place when choosing sites, and focused pilots must show that agronomic and livelihood co-benefits are possible. In the near future, priorities include a 100–200 MWp FPV+storage program on public and industrial reservoirs, province-level agrivoltaic demonstration corridors in Bac Lieu, Soc Trang, and Tra Vinh, mill-anchored biomass CHP with contractual residue baselines, and a storage-enabled distribution reliability package for delta cities..

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