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Multi-Resource Screening and Physics-Based Sizing of a PV–Oscillating Water Column Hybrid Microgrid for Ujong Batee, Indonesia

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ABSTRACT

Coastal energy projects frequently combine all available renewable resources without first testing whether each resource is technically meaningful at the intended scale. This study develops a transparent screening and sizing procedure for a photovoltaic (PV)-oscillating water column (OWC) microgrid in Ujong Batee, Aceh, Indonesia, while explicitly evaluating whether locally measured wind should be retained. Daily solar irradiation and significant wave height-energy period data for April 2024 were reprocessed, and field wind measurements from April-June 2024 were statistically reviewed. Wave power was recalculated from the deep-water energy-flux equation to remove arithmetic inconsistencies in the source table. The corrected mean solar resource was 5.44 ± 0.28 kWh/m²/day, while the wave resource was 14.06 ± 5.66 kW/m for Hs = 1.80 ± 0.45 m and Te = 8.57 ± 1.57 s. The daytime wind series averaged 5.06 ± 0.60 m/s, corresponding to only 79.5 W/m² of gross kinetic power density and lacking nocturnal and hub-height coverage; wind was therefore classified as conditional rather than included in the base design. For a design load of ten 350-W pumps operated for eight hours per day, a 10 m² PV array produces 8.70 kWh/day. At an assumed 12% overall wave-to-wire efficiency, the minimum OWC capture width is 0.48 m, increasing to 0.62 m for a 20% energy reserve. A practical 0.65 m OWC module combined with the PV array yields 35.0 kWh/day and a 25.1% reserve. The main contribution is not merely a hybrid configuration, but a defensible resource-selection rule that prevents low-confidence resources from inflating system performance claims.

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Keywords: *coastal microgrid, hybrid renewable energy, oscillating water column, solar photovoltaic, wave energy*

1. INTRODUCTION

Indonesia's long coastline creates a strong physical case for marine renewable energy, but the technical case for a specific coastal site must still be demonstrated from local data. Wave-energy converters are attractive because ocean waves carry substantially higher power density than wind at the same site and can continue operating after sunset [1], [5]. Among the available conversion concepts, the oscillating water column (OWC) is particularly relevant for nearshore and breakwater applications because its main moving components can be kept above the waterline and the bidirectional air stream can drive a self-rectifying turbine [2], [3]. These characteristics reduce underwater maintenance requirements, although hydrodynamic

resonance, turbine matching, survivability, and conversion losses remain decisive design issues.

Hybridization is often proposed to reduce the intermittency of a single renewable source. Solar PV is mature, modular, and comparatively simple to install, while wave energy offers a different production profile. The combination is therefore appealing for coastal loads such as navigation aids, monitoring stations, cold-chain equipment, and irrigation or aquaculture pumps. However, "more sources" does not automatically mean a better system. Every additional source adds power electronics, structural interfaces, controls, maintenance, and uncertainty. A resource should only be retained when its measured energy density, temporal coverage, and expected conversion performance justify those penalties.

This point is important for Ujong Batee and Gampong Durung in Aceh Besar. Previous local work identified usable solar radiation, an energetic wave climate, and measurable coastal wind. The wind study reported daily values near 4-6 m/s during April-June 2024 [14], but the observations were collected during selected daytime periods rather than at a standard turbine hub height over a complete diurnal cycle. Conversely, the available solar and wave series provide daily data that can be transformed directly into energy metrics. Combining the three resources without first resolving these differences in data quality would create a misleading appearance of precision.

Existing OWC literature provides strong descriptions of hydrodynamics, air-turbine behavior, numerical modeling, and tested prototypes [2]-[4]. Recent reviews also emphasize that capture efficiency is highly site- and geometry-dependent [3], while hybrid offshore wave-PV research is beginning to assess shared infrastructure and complementary generation [10]. Nevertheless, a practical gap remains between resource assessment and small-scale load-oriented sizing: many studies report incident wave power or nominal turbine power without showing the minimum capture width required for a clearly defined load, and without stating which candidate resources were rejected.

This study addresses that gap through a five-stage procedure: data quality control, physics-based resource conversion, resource screening, load definition, and minimum-size calculation. The objective is to determine a defensible PV-OWC configuration for a representative coastal pumping load and to decide whether the available wind data are sufficient for inclusion. The novelty is methodological: the hybrid system is obtained after a resource-selection test, not before it. The specific contributions are (1) correction of wave-power values through full recomputation from Hs and Te; (2) quantitative comparison of solar, wave, and wind data confidence; (3) derivation of the minimum OWC capture width for a defined pump duty; and (4) sensitivity analysis of the result to overall OWC efficiency.

2. METHOD

Study Area and Data Sources

The study area is the Ujong Batee-Gampong Durung coastal corridor in Aceh Besar, Indonesia, near 5°32′20″ N and 95°12′10″ E. The site is exposed to the northern entrance of the Malacca Strait and supports maritime education, coastal settlements, and pond-based production activities. Figure 1 shows the coastal study area, while Table 1 summarizes the datasets and their use in the analysis.



Figure 1. Ujong Batee-Gampong Durung study area in Aceh Besar.

Table 1. Input data and analytical role.

Variable	Period / source	Resolution	Use
Solar irradiation	April 2024; BMKG/ECMWF-derived table	Daily, 30 records	PV energy
Hs and Te	April 2024; ECMWF/WWIII-derived table	Daily, 30 records	Wave flux
Wind speed	Apr-Jun 2024; field measurements [14]	Daytime daily averages, 89 records	Screening only
Pump load	Design scenario	10 × 0.35 kW × 8 h	Sizing target

The analysis uses a screening-level dataset rather than a bankable resource assessment. Solar and wave values are daily, whereas the wind values represent selected daytime measurement windows. This distinction is retained throughout the analysis. No annual energy production, capacity factor, or financial return is claimed from the three-month data.

Quality Control and Statistical Indicators

Each series was checked for missing values, nonphysical ranges, unit consistency, and duplicate arithmetic. Wave power values were not accepted directly from the source table; every record was recalculated from Hs and Te. The mean, sample standard deviation, coefficient of variation, minimum,

and maximum were then computed. The coefficient of variation (CV) was used only as a relative measure of short-period variability, not as a reliability index.

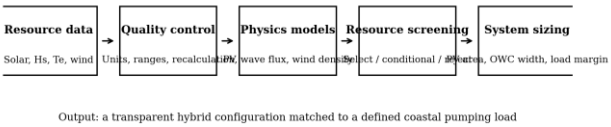


Figure 2. Resource screening and sizing workflow.

Resource Conversion Models

For deep-water irregular waves, the incident energy flux per metre of wave crest is calculated as [1], [5]

$$P_w = (\rho_w g^2 / 64\pi) H_s^2 T_e \quad (1)$$

where Pw is in W/m, ρw = 1025 kg/m³, g = 9.81 m/s², Hs is the significant wave height, and Te is the energy period. Because the local table provides a representative period rather than a spectral energy period, the calculated values are interpreted as screening estimates.

Daily PV energy is calculated from the plane-of-array irradiation using

$$E_{PV} = G_d A_{PV} \eta_{PV} PR \quad (2)$$

where Gd is daily irradiation (kWh/m²/day), APV is module area, ηPV is module efficiency, and PR is the performance ratio representing temperature, wiring, converter, and mismatch losses. The base case uses APV = 10 m², ηPV = 0.20, and PR = 0.80. This formulation corrects the common error of treating daily irradiation as continuous electrical power.

Gross wind power density is used for screening, without converting it into annual turbine energy:

$$P_{d,w} = 0.5 \rho_a v^3 \quad (3)$$

where ρa = 1.225 kg/m³ and v is the measured mean wind speed. A turbine power curve, hub-height correction, and complete wind-speed distribution would be required for a bankable estimate under IEC 61400-2 conditions.

The daily electrical energy from a modular OWC is represented by

$$E_{OWC} = 24 P_w b \eta_{OWC} \quad (4)$$

where b is the effective capture width and ηOWC is the overall wave-to-wire efficiency, including hydrodynamic capture, pneumatic conversion, turbine, generator, and auxiliary losses. A baseline value of 12% is used, with 8-18% sensitivity bounds. This range is deliberately conservative relative to peak laboratory efficiencies because the present study does not include resonance tuning or a measured turbine map [2]-[4], [18].

Load Definition and Sizing Criteria

The design load consists of ten 350-W pumps operating for eight hours per day. The daily energy requirement is therefore

$$E_L = N_p P_p t_p = 10 \times 0.35 \times 8 = 28 \text{ kWh/day} \quad (5)$$

The minimum OWC width is obtained after subtracting PV energy from the required load. A second width is calculated for a 20% design reserve. Energy coverage is defined as C = (EPV + EOWC)/EL. A configuration is considered adequate when C ≥ 1.20 in the screening case. This margin is not a substitute for hourly simulation; it compensates partially for conversion uncertainty and pump-starting losses.

3. RESULTS AND DISCUSSION

Solar and Wave Resource Characteristics

The April solar series is comparatively stable, with a mean of 5.44 kWh/m²/day and a standard deviation of 0.28 kWh/m²/day. The coefficient of variation is only 5.2%, indicating limited day-to-day dispersion during the observed month. For a 10 m² array at 20% module efficiency and PR = 0.80, the expected mean energy is 8.70 kWh/day. The result is approximately 2 kWp of installed module capacity and should not be reported as 5.44 kW of continuous output.

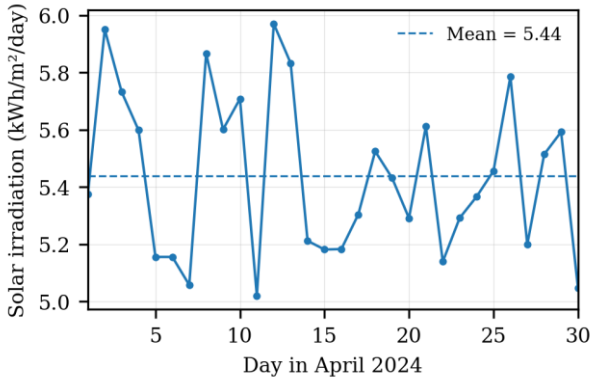


Figure 3. Daily solar irradiation in April 2024.

The wave series has Hs = 1.80 ± 0.45 m and Te = 8.57 ± 1.57 s. Full recomputation gives Pw = 14.06 ± 5.66 kW/m, with a range of 4.49-20.72 kW/m. Quality control identified several stored wave-power values that did not satisfy Equation (1), particularly records with Hs = 2.06 m and Te = 8.6 s. Recalculation raises the monthly mean above the previously reported 11.44 kW/m. This is a material correction because OWC sizing is directly proportional to incident wave power.

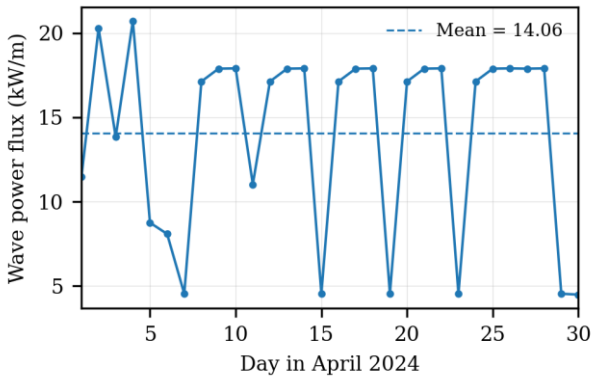


Figure 4. Recalculated daily wave power flux in April 2024.

Table 2. Resource statistics for the available observation periods.

Indicator	Solar	Wave	Wind
Mean	5.44 kWh/m²/d	14.06 kW/m	5.06 m/s
Std. dev.	0.28	5.66	0.60
CV	5.2%	40.3%	11.9%
Observed range	5.02-5.97	4.49-20.72	3.8-6.3

Wind Screening Outcome

The 89 daytime wind records average 5.06 ± 0.60 m/s. Equation (3) gives a gross kinetic power density of 79.5 W/m² at the mean speed. For illustration, a 3 m diameter rotor with Cp = 0.30 and 85% drivetrain efficiency would produce only about 0.14 kW at that mean speed before availability and electrical losses. More importantly, the available records do not represent night-time wind, hub-height flow, turbulence intensity, extreme gusts, or a Weibull distribution. They are sufficient to show that wind exists, but insufficient to support annual-energy or reliability claims.

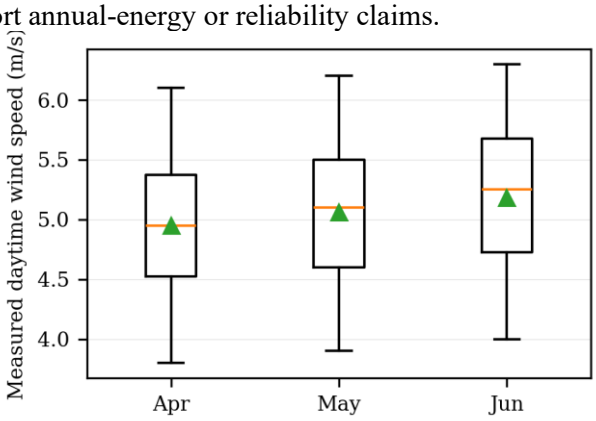


Figure 5. Distribution of measured daytime wind speed by month.

Wind is therefore assigned a conditional status. It should be reconsidered only after at least one year of 10-min measurements at the intended hub height, including data recovery, turbulence, direction, and extreme wind statistics. This decision is not a rejection of wind technology; it is a rejection of overclaiming from a limited dataset. The base system consequently uses PV and OWC, while preserving a DC-bus interface for future wind integration.

Table 3. Multi-resource screening decision.

Criterion	Solar PV	OWC wave	Wind
Data coverage	Daily, 30 d	Daily, 30 d	Daytime windows, 3 mo
Conversion basis	Mature, direct	Physics-based; efficiency uncertain	Power curve unavailable
Temporal role	Daylight energy	Day/night, sea-state dependent	Unknown overnight profile
Decision	Selected	Selected	Conditional / excluded from base

PV-OWC Sizing for the Pumping Load

The 10 m² PV array supplies 8.70 kWh/day, or 31.1% of the 28 kWh/day load. At ηOWC = 12%, a 1 m effective OWC capture width would provide 40.49 kWh/day. The mathematical minimum width after PV contribution is 0.48 m. Requiring a 20% reserve increases the width to 0.61 m. A practical screening choice of 0.65 m yields 26.32 kWh/day from the OWC and 35.02 kWh/day in total, corresponding to an energy-coverage ratio of 1.25 and a reserve of 25.1% relative to the load.

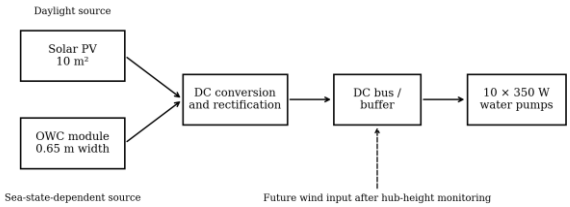


Figure 6. Proposed modular PV-OWC architecture and retained wind interface.

Table 4. Energy-based sizing scenarios.

Configuration	Energy (kWh/d)	Coverage	Assessment
PV only; 10 m²	8.70	0.31	Not adequate
OWC only; b=0.65 m, η=8%	17.55	0.63	Marginal
OWC only; b=0.65 m, η=12%	26.32	0.94	Near load
PV + OWC; b=0.65 m, η=12%	35.02	1.25	Selected
PV + OWC; b=1.0 m, η=12%	49.20	1.76	Scalable reserve

Sensitivity, Interpretation, and Implementation Limits

The OWC result is most sensitive to overall efficiency because the current dataset describes incident wave energy, not measured wave-to-wire output. Figure 7 shows that the required width for a 20% reserve decreases from approximately 0.92 m at 8% efficiency to 0.41 m at 18%. The selected 0.65 m width is therefore defensible only around the 12% baseline. If prototype testing demonstrates lower efficiency, the capture width must be increased rather than compensating with optimistic operating hours.

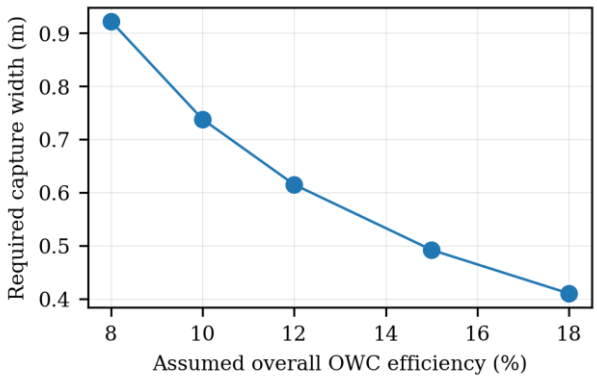


Figure 7. OWC capture width required for a 20% energy reserve.

Table 5. Sensitivity to overall wave-to-wire efficiency.

ηOWC	Width for 20% reserve (m)	Energy at b=0.65 m (kWh/d)
8%	0.92	26.25
10%	0.74	30.64
12%	0.61	35.02
15%	0.49	41.60
18%	0.41	48.18

Three implementation limitations must be stated clearly. First, one month of solar-wave data cannot represent monsoon-season variability or extreme sea states. Second, daily energy balance does not resolve pump starting current, short-duration wave lulls, or converter dynamics; an hourly or sub-hourly dispatch model and a small battery or supercapacitor buffer are required for detailed design. A two-hour pump buffer would require approximately 8.8 kWh of nominal battery capacity at 80% usable depth of discharge. Third, capture width is an energy-normalized parameter, not a complete chamber geometry. CFD and wave-tank testing are required to determine chamber draft, opening height, resonance, air-duct diameter, turbine damping, and structural loads.

Despite these limits, the method provides a more credible starting point than adding resources based solely on their physical presence. The corrected wave calculation, realistic PV conversion, explicit load definition, and conditional treatment of wind make the design auditable. The next research stage should use at least one year of ERA5 or buoy-calibrated wave data, year-round hub-height wind monitoring, CFD-based OWC geometry optimization, and hardware-in-the-loop testing of the common DC bus.

4. CONCLUSION

This study demonstrates that a hybrid renewable system should be selected through resource screening rather than by automatically combining every locally available source. For Ujong Batee, the April 2024 solar resource is stable at 5.44 ± 0.28 kWh/m²/day, while corrected wave-power calculations yield 14.06 ± 5.66 kW/m. The available wind measurements average 5.06 ± 0.60 m/s during daytime windows, but their temporal and vertical coverage are insufficient for annual-energy or reliability estimation. Wind is therefore retained as a future auxiliary option, not as a base-design contributor. A 10 m² PV array supplies 8.70 kWh/day. For ten 350-W pumps operated eight hours per day, the minimum OWC capture width is 0.48 m at 12% overall efficiency, or 0.62 m when a 20% reserve is required. A 0.65 m module combined with PV produces an estimated 35.0 kWh/day, giving 25.1% reserve over the defined 28 kWh/day load. These values are screening results, not bankable production guarantees. Their main value is a transparent design logic that can be updated directly when longer resource series, CFD-derived efficiency, and prototype measurements become available.

DATA AVAILABILITY AND AUTHOR RESPONSIBILITY

The numerical series used in this manuscript are contained in the authors' prior research tables and were reprocessed in this study. Official reanalysis and wave-model products remain subject to their respective provider terms. Before submission, all listed authors should verify authorship contributions, dataset provenance, and the final numerical tables.

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