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Article

Future-Proofing Renewable Energy Systems: A Multi-Dimensional Resiliency Framework for Island Grids under Extreme Demand Stress

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Abstract: Objectives: To develop and empirically validate a multi-dimensional resiliency assessment framework for renewable-rich island power systems subjected to extreme real-world grid stress, using the isolated Mindanao grid of the Philippines during the 2020 demand disturbance as a full-scale natural experiment. Methods: Six years (2015 to 2020) of official operational records from the system operator, the Department of Energy, and utility regulatory reports were consolidated, covering monthly energy delivery, system peak demand, 366 days of daily supply-demand balance, generation and rated capacity by fuel type, average system rates of more than thirty distribution utilities, and the reliability indices SAIFI, SAIDI, and MAIFI. Resiliency was evaluated across four dimensions, namely operational, generation, economic, and infrastructure, through pre-disturbance and during-disturbance comparative analysis. Findings: The disturbance compressed monthly energy delivery by up to 9.3% and April peak demand by 11.6% year-on-year, yet annual energy delivery contracted by only 1.0% (10,180 GWh to 10,075 GWh) and annual generation by 0.4%. Renewable generation adapted flexibly: hydro output fell 10.3% while solar and biomass output rose 18.7% and 17.9%, respectively. The mean daily reserve margin widened from 44.4% in 2019 to 58.0% in 2020, average distribution rates declined 4.5% to PhP 9.35/kWh, and reliability improved, with SAIFI, SAIDI, and MAIFI changing by −4.3%, −4.3%, and −20.7%, respectively. All four dimensions were maintained or improved, demonstrating system-level resiliency. Novelty: The study transforms a once-in-a-generation real-world disturbance into a reusable four- dimension resiliency assessment framework, validated entirely with measured operational data, that is applicable to future extreme stress scenarios such as cyberattacks, climate-induced disasters, and fuel crises in islanded and developing renewable-dominant power systems.
Keywords: Power System Resiliency, Renewable Energy, Island Grid, Extreme Grid Stress, Reli- ability Indices, Mindanao

1 Introduction

Power systems worldwide are entering an era of escalating uncertainty in which climate-related disasters, cyber-physical attacks, fuel supply disruptions, rapid electrification, and public health emergencies impose stresses that differ substantially from those considered in conventional planning, making resiliency a defining challenge of the global energy transition [1]. Current practice offers a broad menu of resilience concepts and enhancement strategies, but their operationalization for real systems remains an open problem [2], and growing renewable penetration compounds the difficulty by introducing operational variability while reducing dependence on dispatchable centralized generation [3]. The 2020 pandemic containment measures produced the largest unplanned full-scale stress test of modern grids: consumption in European countries fell by 14% to 25% under strict lockdowns [4], with measurable distortions of grid dynamics across the continent [5] and marked shifts in the residual load and market outcomes of the German and neighboring systems [6]. In the United States, cross-domain analyses quantified consumption reductions of roughly 6% to 10% with altered daily load shapes [7, 8], while global assessments documented demand contraction, renewable share gains, and emerging operational challenges [9, 10], emergency tariff interventions to protect consumers [11], and consequences for the politics of energy transitions [12]. Three gaps persist in this literature. First, power system resilience is still quantified predominantly through simulation-based or scenario-based metrics rather than measured disturbance data [13], and taxonomies of energy resilience remain largely conceptual [14]. Second, nearly all empirical pandemic studies examined large interconnected systems in advanced economies, leaving isolated island grids in developing countries, which face the disturbance without the buffer of interconnection imports, essentially undocumented. Third, existing studies were framed as descriptive impact assessments of a specific event rather than as framework-generating analyses that remain applicable to future stresses. The stress categories motivating this study are each independently documented in the literature. Recent comprehensive reviews confirm that power system resilience concepts, metrics, and enhancement measures remain an active and unsettled research frontier [18, 19, 20, 21, 22, 23, 24], with particular attention to resilience against climate-driven extreme weather [27, 28, 29, 30, 31], cyberattacks and cyber-physical vulnerabilities [32, 33, 34, 35, 36, 37, 38, 39], and the special difficulties of maintaining resilience in renewable-dominant systems under high-impact low-frequency events [19, 21]. Within this broader landscape, island and archipelagic power systems occupy a distinct position: their electrical isolation removes the interconnection buffer available to continental grids, so locally sourced flexibility from storage and generation control becomes the primary resilience mechanism [40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50]. The Philippines exemplifies this challenge, with ongoing national efforts to raise renewable penetration across its three island grids while managing legacy reliability and cost constraints [25, 26]. This study addresses these gaps by treating the 2020 demand collapse not as the subject of investigation but as a natural experiment that reveals how a renewable-rich, fully islanded grid behaves under extreme systemic stress. The objectives are: (1) to develop a multi-dimensional resiliency framework for renewable energy systems operating under extreme grid stress; (2) to em- pirically evaluate the resiliency of the Mindanao island grid using actual operational data collected before and during the large-scale demand disturbance; and (3) to identify structural characteristics that enhance renewable energy resilience and translate them into planning recommendations for islanded and developing power systems.

2 Methodology

2.1 Study System and Data Sources

The study system is the Mindanao grid, the southern island grid of the Philippines, which operated in complete electrical isolation from the Luzon–Visayas system throughout the study period. In 2020, the grid had a rated capacity of about 4,519 MW from coal, oil-based, geothermal, hydro, solar, and biomass plants, against a historical maximum peak demand of 2,013 MW recorded in May 2019. Community quarantine measures were enforced beginning 16 March 2020, providing a sharply defined disturbance onset. Six datasets were consolidated from official sources [15, 16]: (i) monthly energy delivery for 2015 to 2020 from system operator records; (ii) monthly system peak demand for 2013 to 2020; (iii) daily supply-demand balance for all 366 days of 2020 and the corresponding days of 2019, comprising rated capacity, available capacity, daily peak demand, gross reserve, and gross generation; (iv) monthly generation and rated capacity per fuel type for 2018 to 2020; (v) historical average system rates of private distribution utilities and electric cooperatives across the six Mindanao regions for 2016 to 2020, taken from monthly operations and financial-statistical reports; and (vi) the reliability indices SAIFI, SAIDI, and MAIFI of twenty distribution utilities for 2015 to 2020.

2.2 Multi-Dimensional Resiliency Framework

Resiliency is treated as the ability of the power system to maintain its essential functions when subjected to an extreme disturbance, consistent with operational and infrastructure resilience quantification concepts [17]. Four dimensions are defined, each answering one guiding question and each mapped to measurable indicators available from routine operational reporting, as summarized in Table 1 and illustrated in Figure 1. Operational resilience asks whether electricity continues flowing despite sudden demand disruption and is measured through energy delivery, peak demand, and the daily supply-demand balance. Generation resilience asks whether the generation portfolio, particularly its renewable component, can adapt without compromising adequacy, and is measured through the fuel mix, renewable penetration, and installed capacity. Economic resilience asks whether electricity remains economically sustainable during the crisis and is measured through distribution rates. Infrastructure resilience asks whether the physical network continues delivering reliable electricity and is measured through SAIFI, SAIDI, and MAIFI. The framework is deliberately built on indicators that any system operator and regulator already publish, so that it can be replicated in other jurisdictions without specialized instrumentation.

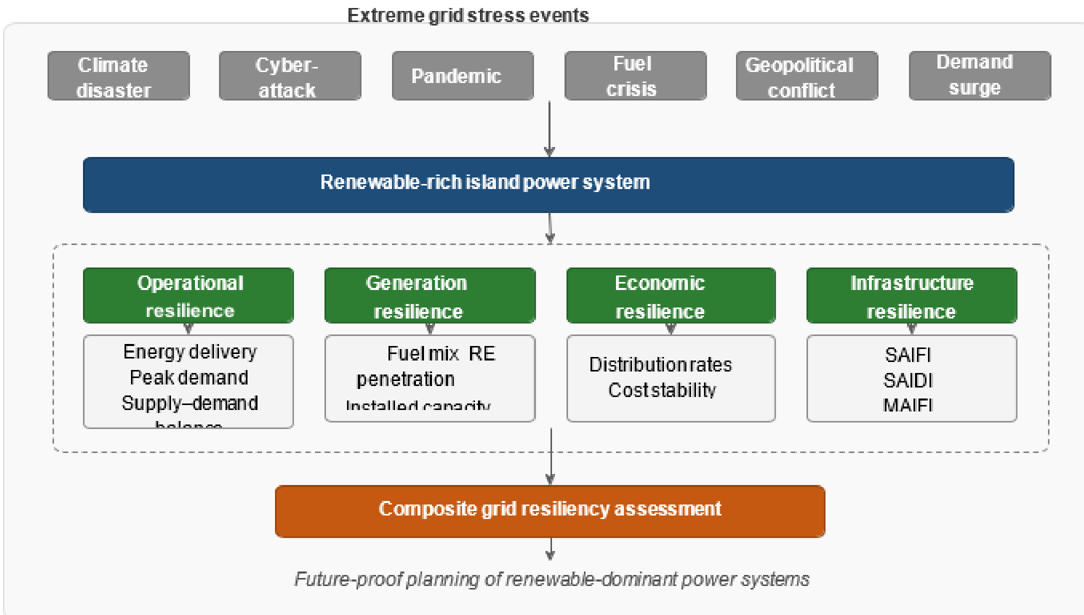

Figure 1: Multi-dimensional resiliency framework for renewable energy systems under extreme grid stress.

Table 1: Four dimensions of the renewable energy resiliency framework

Dimension	Guiding question	Indicators	Data source and period
Operational	Can electricity continue flowing despite sudden demand disruption?	Monthly energy delivery; system peak demand; daily supply-demand balance and gross reserve	System operator records, 2015–2020 (daily for 2019–2020)
Generation	Can renewable generation adapt without compromising adequacy?	Generation per fuel type; renewable penetration; rated capacity per fuel type	Department of Energy power statistics, 2018–2020
Economic	Can electricity remain economically sustainable during crisis?	Average system rates of private utilities and electric cooperatives by region	Monthly operations and financial-statistical reports, 2016–2020
Infrastructure	Can the physical network continue delivering reliable electricity?	SAIFI; SAIDI; MAIFI (20 distribution utilities, Mindanao average)	Utility reliability reporting, 2015–2020

2.3 *Analytical Procedure*

The five years 2015 to 2019 serve as the pre-disturbance baseline and 2020 as the disturbance year, with the enhanced community quarantine window (days 76 to 152 of 2020) analyzed separately. For every indicator *X* of dimension *i*, the year-on-year relative change is computed as

$$\Delta X\,(\%) = \frac{X_{2020} - X_{2019}}{X_{2019}} \times 100 \qquad (1)$$

and the daily reserve margin on day *d* is computed from available capacity *C* and daily peak demand *P* as

$$RM_d\,(\%) = \frac{C_d - P_d}{P_d} \times 100 \qquad (2)$$

A dimension is judged resilient when its indicators remain within, or recover to, the envelope of the baseline years despite the disturbance. Renewable penetration is computed as the share of geothermal, hydro, solar, and biomass generation in gross generation. All computations were performed directly on the consolidated official records without smoothing or imputation.

3 Results and Discussion

3.1 Operational Resilience

Figure 2 shows monthly energy delivery for Mindanao from 2015 to 2020. The first quarter of 2020 tracked a strong growth trajectory, with January to March delivery up 5.9%, 11.5%, and 10.3% year-on-year. The quarantine measures then produced the deepest contraction in the record: April delivery fell 9.3% and May 8.4% year-on-year. The rebound, however, was rapid and nearly monotonic; the year-on-year gap narrowed each month until November delivery turned positive (+0.3%). The demand shock was therefore an elastic deformation rather than a structural break: annual delivery contracted only 1.04%, from 10,180 GWh in 2019 to 10,075 GWh in 2020, a level still 6.4% above the 2015 to 2019 average. This trajectory is markedly milder than the 14% to 25% national contractions measured in strictly locked-down European systems [4, 5] and is comparable to the 6% to 10% reductions of United States markets [7, 8], which is attributable to the residential- heavy, cooling-driven load composition of the island: consumption suppressed in commercial and industrial feeders partially migrated into households under stay-at-home conditions.

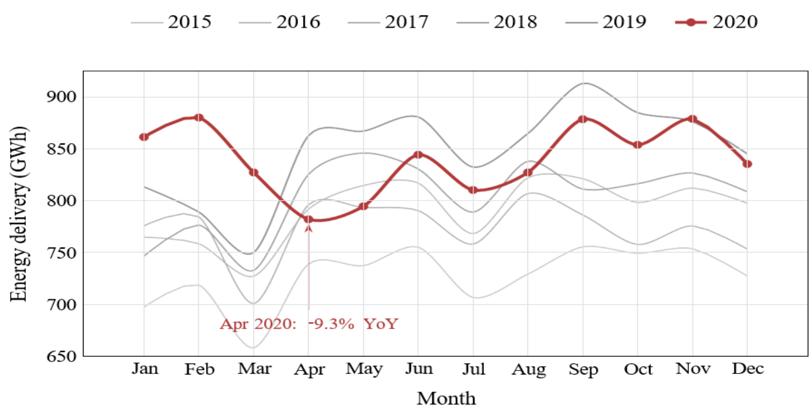

Figure 2: Monthly energy delivery of the Mindanao grid, 2015 to 2020.

Figure 2: Monthly energy delivery of the Mindanao grid, 2015 to 2020.

Peak demand exhibits the same signature (Figure 3a). Mindanao set an all-time record of 1,977 MW in February 2020, immediately before the disturbance, then dropped to 1,673 MW in April, a year-on-year contraction of 11.6% and the first negative annual peak growth in the eight- year record (−1.8%, versus +8.6% in 2019). The daily balance for all 366 days of 2020 (Figure 3b) demonstrates why adequacy was never threatened: the minimum daily peak during the quarantine window fell to 1,390 MW while available capacity remained between roughly 2,500 MW and 3,100 MW, so that the mean daily reserve margin widened from 49.8% before the lockdown to 56.1% during the enhanced community quarantine and averaged 58.0% for the year, against 44.4% in 2019. The disturbance thus paradoxically strengthened short-term adequacy by flattening load, converting a demand crisis into reserve headroom, an effect also inferred, though not measured at daily granularity, for interconnected European systems [6].

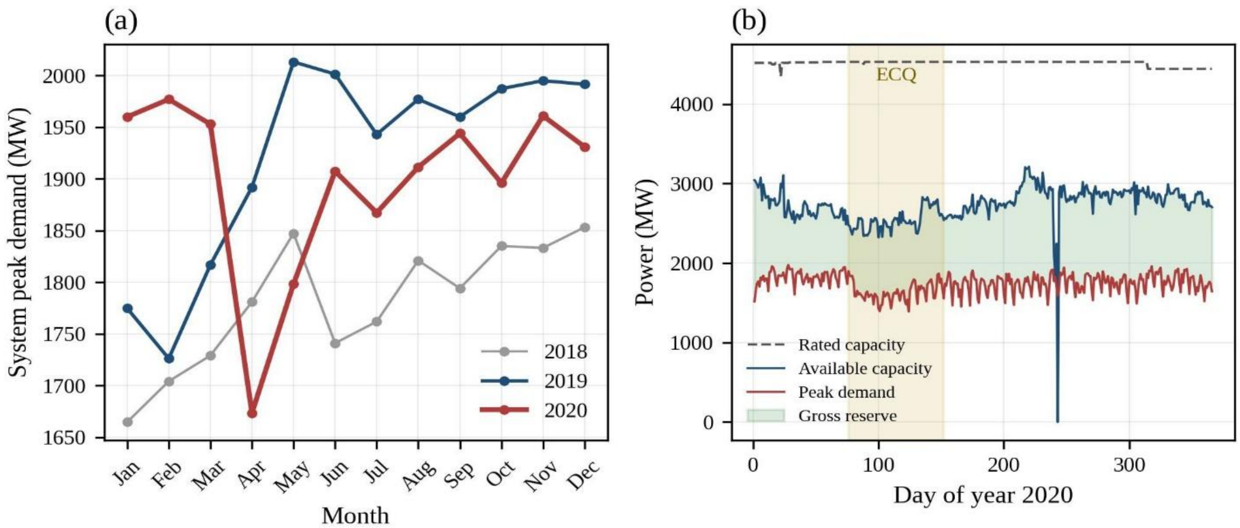

Figure 3: (a) Monthly system peak demand, 2018 to 2020; (b) daily supply-demand balance of Mindanao in 2020.

3.2 Generation Resilience

Gross generation was almost unchanged at the annual scale, declining only 0.38% from 12,655 GWh in 2019 to 12,607 GWh in 2020, but its composition reorganized along the merit order (Figure 4a). Baseload coal output rose 4.9%, absorbing the largest share of the reduced demand under bilateral contract structures and the 46.5% coal capacity expansion completed in 2019 (1,545 MW to 2,263 MW). Oil-based peaking generation, the marginal and most expensive resource, collapsed by 52.8%, exactly as dispatch hierarchy predicts when peak demand contracts. Within the renewable portfolio, the response was heterogeneous: hydro fell 10.3%, reflecting reservoir and hydrological conditions in early 2020 rather than the demand shock; geothermal declined 3.3%, while solar and biomass grew 18.7% and 17.9%, respectively, and were dispatched in full throughout the disturbance under priority-dispatch rules. Renewable penetration consequently fell from 38.1% of gross generation in 2018 to 29.8% in 2019 and 27.7% in 2020 (Figure 4b); this decline is structural, driven by the coal build-out and hydro shortfall, and predates the pandemic.

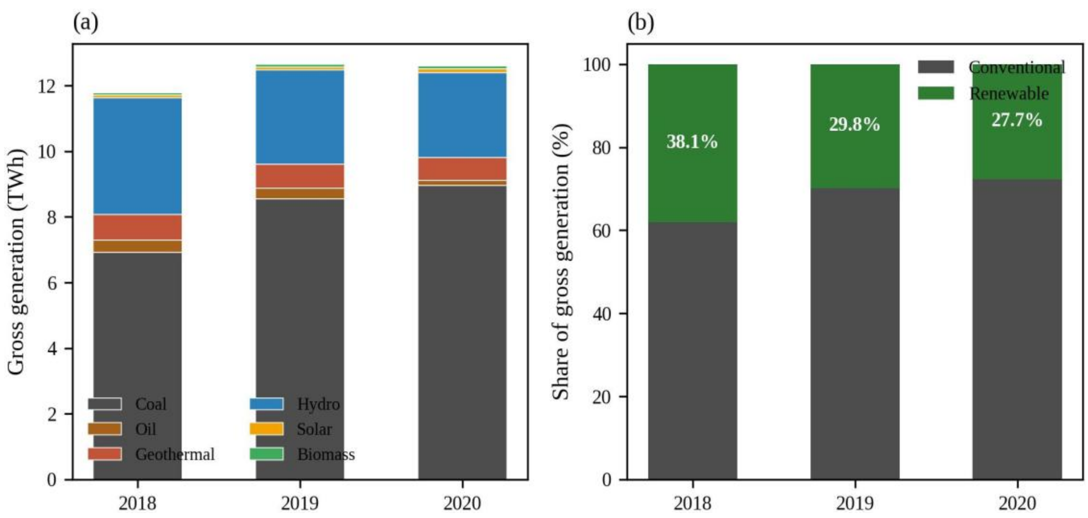

Figure 4: (a) Annual gross generation by fuel type; (b) conventional versus renewable generation share.

The system-level flexibility documented here is underpinned by mechanisms studied at the plant and microgrid level. Droop-based and virtual-impedance control schemes for renewable- integrated islanded microgrids have been shown to improve power-sharing accuracy and damp frequency oscillations under variable wind and solar output [45, 46, 47], while decentralized architectures incorporating virtual synchronous machines and distributed optimization further stabilize frequency and voltage during economic dispatch transitions [48, 49, 50]. Battery energy storage is increasingly recognized as a complementary resource for this kind of flexibility, both for primary frequency response and for absorbing curtailed renewable energy that would otherwise be wasted during periods of subdued demand [44, 41, 42, 43, 40]. Although the Mindanao grid analyzed here relies on conventional droop-governed synchronous generation rather than inverter-based control, the same underlying principle applies: technical characteristics that improve fine-grained power- sharing and frequency stability at the plant level are what allow the aggregate system observed in Figure 3b to absorb a demand shock without exceeding its reserve margin.

Two conclusions follow. First, variable renewable generation on the island absorbed the extreme demand disturbance without curtailment-driven instability, in contrast with the renewable- management challenges reported for high-penetration European systems during the same period [6, 10]. Second, the disturbance exposed a fuel-dependency risk: the system's flexibility was provided almost entirely by displacing oil-based plants, so a grid with a higher inflexible baseload share and lower dispatchable renewable capacity would have had materially less room to maneuver.

3.3 Economic Resilience

Average system rates of Mindanao distribution utilities are shown in Figure 5. The Mindanao-wide average declined 4.5% during the disturbance year, from PhP 9.79/kWh in 2019 to PhP 9.35/kWh in 2020, continuing a downward correction that began in 2019 after the 2018 peak of PhP 10.14/kWh. Electric cooperatives, which serve the most vulnerable consumers, recorded a 4.4% decline, and private utilities 1.8%. Rate stability was achieved without the emergency tariff interventions that many jurisdictions were forced to adopt during the pandemic [11]. The insulation is architectural: the predominance of long-term power purchase agreements and cost-based bilateral contracts in Mindanao decouples retail rates from short-run demand volatility, so the demand collapse did not propagate into price shocks. Rates therefore acted as an economic shock absorber, sustaining affordability precisely when household incomes were most stressed, which is the essential requirement of economic resilience.

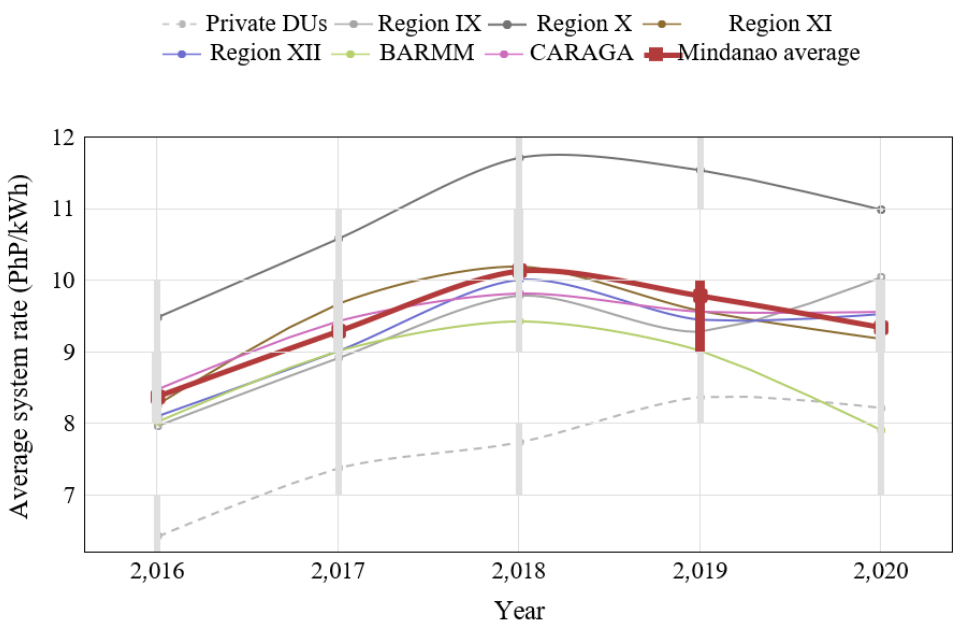

Figure 5: Average system rates of Mindanao distribution utilities, 2016 to 2020.

3.4 Infrastructure Resilience

Figure 6 presents the Mindanao averages of the three reliability indices across twenty distribution utilities. All three improved during the disturbance year: SAIFI fell 4.3% to 9.61 interruptions per customer, SAIDI fell 4.3% to 553.1 minutes per customer, and MAIFI, the momentary interruption index, recorded its largest improvement in the six-year series at −20.7%, dropping to 10.50 interruptions per customer. These 2020 gains extend a maturation trend visible since 2018, when SAIDI improved 33.5% in a single year, but the disproportionate MAIFI improvement is a disturbance signature: flattened loading reduced feeder congestion and thermal stress, suppressing the transient faults that dominate momentary interruptions, while curtailed economic activity created maintenance windows. The physical network therefore continued delivering, and in fact improved, reliable electricity throughout the stress event, completing the fourth dimension of the framework.

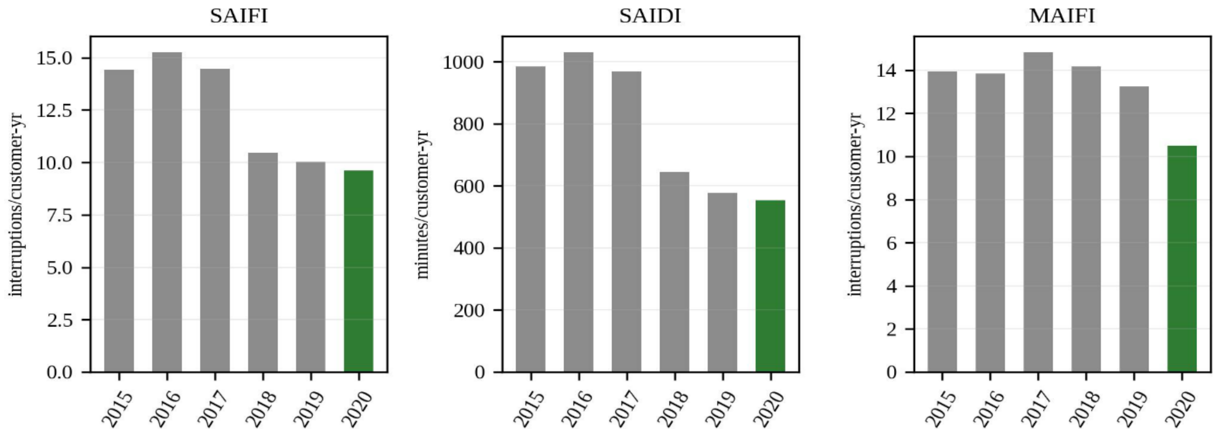

Figure 6: Mindanao average reliability indices SAIFI, SAIDI, and MAIFI, 2015 to 2020.

3.5 Synthesis and Framework Implications

Table 2 consolidates the four dimensions. Every indicator either remained within its baseline envelope or improved: annual energy delivery −1.0%, annual maximum peak −1.8%, generation

−0.4%, reserve margin +13.6 percentage points, rates −4.5%, and all three reliability indices negative (improving). Against the guiding questions of the framework, the Mindanao grid maintained electricity flow, adapted its generation portfolio, preserved affordability, and improved network reliability, and is therefore assessed as resilient across all four dimensions under an extreme, real- world systemic stress.

Table 2: Summary of resiliency indicators of the Mindanao grid, 2019 versus 2020

Dimension	Indicator	2019	2020	Change (%)
Operational	Annual energy delivery	10,180.2	10,074.6	−1.04
	(GWh)			
	Deepest monthly contraction	862.7	782.1	−9.34
	(April, GWh)			
	Annual maximum peak de-	2,013.2	1,977.0	−1.80
	mand (MW)			
	April peak demand (MW)	1,892.0	1,673.4	−11.55
	Mean daily reserve margin	44.4	58.0	+13.6 pp
	(%)			
Generation	Gross generation (GWh)	12,655.4	12,607.4	−0.38
	Oil-based generation (GWh)	331.9	156.8	−52.77
	Hydro generation (GWh)	2,881.6	2,585.2	−10.28
	Solar generation (GWh)	89.1	105.7	+18.70

	Biomass generation (GWh)	84.4	99.5	+17.89
	Renewable penetration (%	29.8	27.7	−2.1 pp
	of generation)			
Economic	Average system rate	9.79	9.35	−4.52
	(PhP/kWh)			
Infrastructure	SAIFI (interrup-	10.04	9.61	−4.29
	tions/customer)			
	SAIDI (minutes/customer)	577.8	553.1	−4.29
	MAIFI (interrup-	13.23	10.50	−20.65
	tions/customer)			

The contribution of this result is methodological as much as empirical: whereas previous pandemic-period studies quantified impacts on large interconnected systems [4, 5, 6, 7, 8, 9, 10], the present study demonstrates that a compact, replicable set of routinely published indicators is sufficient to render a defensible, multi-dimensional resiliency verdict for an isolated island grid. Although the framework is validated here with the 2020 demand disturbance, none of its elements is pandemic-specific: comparable demand distortions may emerge from cyberattacks, artificial- intelligence-driven industrial demand growth, geopolitical fuel disruptions, climate-induced dis- asters, or prolonged transmission failures, and the framework applies unchanged to any of them. Three structural characteristics identified here should be deliberately engineered into future island grids: wide reserve adequacy relative to peak demand, a diversified renewable portfolio in which dispatchable renewables complement variable ones, and long-term contract architectures that insulate consumers from short-run volatility.

4 Conclusion

This study converted the 2020 demand collapse on the isolated Mindanao grid into a reusable, empirically validated multi-dimensional resiliency assessment framework for renewable-rich island power systems, fulfilling all three objectives. Operationally, the grid absorbed a monthly demand contraction of up to 9.3% in energy and 11.6% in peak while limiting annual losses to 1.0% and 1.8%, respectively, and widening its mean daily reserve margin from 44.4% to 58.0%. In generation, annual output changed only −0.4% while the portfolio re-balanced along the merit order, with oil-based generation falling 52.8% and solar and biomass rising 18.7% and 17.9%. Economically, average rates declined 4.5% to PhP 9.35/kWh without emergency intervention, and in infrastructure, SAIFI, SAIDI, and MAIFI improved by 4.3%, 4.3%, and 20.7%.

The novelty of the work is the demonstration, using measured rather than simulated disturbance data, that four dimensions built entirely from routinely published indicators suffice to assess island-grid resiliency, and that the resulting framework generalizes beyond its validating event to any extreme grid stress. Knowledge gaps remain: the assessment covers a single grid and a single demand-side disturbance, uses aggregated reliability indices annually, and does not capture frequency or voltage dynamics; the observed renewable penetration decline (38.1% in 2018 to 27.7% in 2020) shows that resiliency was partly purchased with increased fossil dependence, a trade-off the framework records but cannot yet optimize. Future work should extend the framework toward battery energy storage, microgrids, hydrogen integration, inverter-based resources, probabilistic resilience quantification, artificial-intelligence-assisted dispatch, and digital-twin replication of the disturbance, and should apply it comparatively to other island and developing grids to establish resiliency benchmarks.

5 Data Availability Statement

All data used in this study were derived from official publicly reported records of the Philippine Department of Energy, the system operator, and distribution utility regulatory reports (monthly operations reports and monthly financial and statistical reports). The consolidated dataset supporting the findings is available from the corresponding author upon reasonable request.

6 Details of Ethical Clearance

This study analyzed secondary, aggregated power system operational data only. It did not involve human participants, animal subjects, or personally identifiable information; hence, ethical clearance is not applicable.

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