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RESEARCH ARTICLE

Renewable Energy Grid Integration Challenges in Island Nation Power Systems

Helen Sorensen^{1*}, Carla Andersson² and Rui Georgiou³¹Department of Environmental Science and Sustainability, Alpine Institute of Environmental Sciences, Austria²Department of Environmental Science and Sustainability, Loire University Center for Climate Data Analysis, France³Department of Climate Science, Shannon University Centre for Ecology and Biodiversity, Ireland*Corresponding author: Helen Sorensen, Department of Environmental Science and Sustainability, Alpine Institute of Environmental Sciences, Austria; Email: h.sorensen@aies.at

ABSTRACT

Small, electrically isolated island grids are frequently cited as ideal proving grounds for high-penetration renewable energy, yet the same characteristics that make islands attractive for decarbonisation, small system size, limited interconnection, and high delivered electricity costs, also make them unusually vulnerable to the frequency stability and curtailment problems that variable solar and wind generation introduce. We compiled operational data (2016-2023) from eight island power systems ranging in installed capacity from 6 MW to 210 MW, spanning the Mediterranean, Caribbean, Atlantic, Pacific and Southern Ocean, and analysed one-minute frequency records, dispatch logs and curtailment reports against each system's instantaneous variable renewable energy (vRE) penetration to characterise the relationship between penetration level, system inertia, and operational reliability. Across the sample, annual vRE curtailment rose approximately linearly with average annual penetration once penetration exceeded roughly 30%, reaching a median of 18% of available vRE energy at the three highest-penetration systems (annual average 42-61%), and instantaneous penetration above 65% was associated with a more than fourfold increase in the frequency of under-frequency load-shedding events relative to periods below 40% instantaneous penetration. Systems that paired high vRE shares with fast-responding battery storage sized above roughly 15% of peak demand sustained instantaneous penetration exceeding 80% for cumulative periods of several hundred hours per year with frequency nadirs remaining within statutory limits, while systems lacking comparable storage or synthetic inertia provision required conservative synchronous-generator minimum-loading rules that constrained vRE penetration well below the resource's technical potential. We found no single penetration threshold beyond which stability degraded uniformly; rather, the effective ceiling was set jointly by minimum system inertia, storage power and duration, and the flexibility of remaining thermal plant. These results suggest that island decarbonisation targets expressed purely as an annual renewable energy share understate the operational engineering required to reach them reliably, and that storage sizing and inertia provision, not generation capacity alone, are the binding constraints on how far island systems can practically be pushed toward full renewable supply.

Keywords: island power systems; variable renewable energy; grid frequency stability; system inertia; curtailment; battery energy storage; small isolated grids; energy transition

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1. INTRODUCTION

Island nations and other electrically isolated territories occupy an unusual position in the global energy transition. Many have among the highest per-kilowatt-hour electricity costs in the world, owing to dependence on imported diesel or heavy fuel oil, and simultaneously possess strong indigenous solar and wind resources, making the economic case for renewable deployment often more favourable than on large interconnected continental grids [1,2]. Numerous islands have consequently set renewable energy targets at or approaching 100% of annual electricity supply, and several small systems already operate with annual variable renewable energy shares above 40% [3,4].

What is less widely appreciated outside the power systems engineering literature is that the same isolation that motivates island decarbonisation also removes the principal tool continental grids use to absorb renewable variability, namely the ability to import or export power across a large synchronous or HVDC-interconnected area [5,6]. A continental grid experiencing a sudden cloud-driven drop in solar output draws on inertia and reserve distributed across thousands of megawatts of interconnected plant; an island grid with a peak demand of 20-50 MW has no such buffer, and the same percentage drop in solar output can represent a swing of several megawatts against a total system inertia equivalent to only a handful of synchronous generators [7,8].

This isolation manifests as two distinct but related operational problems. The first is frequency stability: as synchronous thermal generation is displaced by inverter-based solar and wind, system inertia and primary frequency response capability decline, and the rate of change of frequency following a generation or load disturbance increases, raising the risk that protection relays trip generators or shed load before slower reserves can respond [9,10]. The second is curtailment: because island demand is small and storage historically limited, periods of high renewable output routinely exceed what the system can absorb while keeping enough synchronous plant online to maintain adequate inertia and reserve, forcing operators to curtail otherwise-available solar or wind energy rather than risk instability [11,12]. Both problems worsen, though not necessarily in the same proportion, as annual renewable penetration rises.

A substantial case-study literature documents these dynamics for individual islands, including hybrid wind-pumped-storage systems in the Aegean [13,14], battery-firmed solar-diesel systems in the Caribbean and Pacific [15], and combined wind-solar-hydro-battery systems approaching full renewable supply in Atlantic and Southern Ocean settings [3,16]. What remains comparatively rare is a cross-system analysis that places island grids of different size, resource mix, and storage configuration on a common operational basis, in order to

ask whether general relationships exist between penetration level, inertia, storage, and reliability outcomes, or whether each island's experience is essentially idiosyncratic.

This study assembles multi-year operational data from eight island power systems with differing renewable technology mixes and storage deployments and asks three questions. First, how does annual curtailment scale with average vRE penetration across systems of different size and storage configuration? Second, what is the relationship between instantaneous vRE penetration, system inertia, and the incidence of frequency excursions and under-frequency load-shedding? Third, do systems that deploy fast-responding storage or synthetic inertia achieve materially higher sustainable penetration ceilings than those relying on conventional synchronous plant alone? We use these results to characterise the operational engineering constraints that stand between an island's stated renewable energy target and its reliable achievement.

2. MATERIALS AND METHODS

We compiled and analysed operational data from eight island electricity systems for the period 2016-2023, combining one-minute system frequency records, generator and storage dispatch logs, and published curtailment and renewable energy statistics, to characterise the relationship between variable renewable energy penetration, system inertia, storage deployment, and reliability outcomes across systems of differing size and configuration.

2.1 Island system selection and data sources

Eight island power systems were selected to span a range of installed capacity (6-210 MW), renewable technology mix (wind-dominated, solar-dominated, and mixed wind-solar-hydro systems), and storage deployment (none, lithium-ion battery, and pumped hydro), while requiring that each system publish or make available to us, under research data-sharing agreements with the respective utility or system operator, at least three continuous years of one-minute frequency data and daily or better resolution generation-by-source and curtailment records within the 2016-2023 study window. Systems with less than 18 months of usable frequency data, or with material interconnection to a neighbouring grid during the study period, were excluded to keep the comparison restricted to genuinely isolated systems.

2.2 Frequency and dispatch data processing

One-minute average system frequency, instantaneous vRE penetration (wind plus solar generation as a percentage of simultaneous system load), and online synchronous generating capacity were merged into a common analysis table for each system, with timestamps converted to local standard time and daylight-saving transitions checked manually. Frequency excursion events were defined as any one-minute interval in which system frequency departed from nominal by more than

the system's published normal operating band (typically ± 0.2 Hz for 50 Hz systems and ± 0.36 Hz for 60 Hz systems), and under-frequency load-shedding events were identified from utility incident logs and cross-checked against frequency records showing the associated step recovery.

2.3 Estimating system inertia and effective penetration ceiling

Instantaneous system inertia was estimated from the online synchronous generator fleet at each one-minute interval using manufacturer-published inertia constants (H , in MW·s/MVA) for each unit type, summed and weighted by online rated capacity; this is an approximation, since it does not capture inertia contributions from synchronous condensers or grid-forming inverter control where deployed, both of which were treated separately for the two systems where they were present. For each system we then defined the sustainable penetration ceiling empirically as the highest instantaneous vRE penetration sustained for at least 30 consecutive minutes without a frequency excursion event, evaluated separately for each calendar quarter to capture any change in ceiling over the study period as storage or inertia provision was added.

2.4 Curtailment accounting

Curtailed vRE energy was taken directly from utility or system operator curtailment logs where published as a distinct category (five of eight systems); for the remaining three systems, curtailment was estimated as the difference between modelled uncurtailed generation, reconstructed from co-located irradiance or wind speed records and each plant's rated power curve, and the plant's actual metered output, a method whose uncertainty we bound by comparing it against the directly reported figures at the five systems where both were available, finding a mean absolute discrepancy of 2.1 percentage points of annual vRE energy.

2.5 Storage and synthetic inertia characterisation

For each system with battery or pumped-hydro storage, we recorded nameplate power (MW) and usable energy capacity (MWh), expressed storage power as a percentage of system peak demand, and classified each storage asset's control mode (frequency-responsive fast reserve, scheduled energy arbitrage, or both) from utility operating documentation. Where grid-forming inverter control or synthetic inertia provision from battery or wind assets was in use, we noted the manufacturer-stated equivalent inertia contribution, though we treat these figures as indicative rather than independently verified, since manufacturer synthetic inertia specifications are derived from factory testing rather than in-field measurement at the specific sites studied.

2.6 Statistical analysis

The relationship between average annual vRE penetration and annual curtailment fraction was assessed by ordinary least squares regression pooling all system-years ($n=52$), with a piecewise linear

specification allowing the slope to change at a breakpoint estimated by grid search over candidate penetration values. The relationship between instantaneous penetration band and frequency excursion incidence was assessed by comparing excursion counts per operating hour across four penetration bands (below 40%, 40-55%, 55-65%, above 65%) using a negative binomial regression with system fixed effects to account for baseline differences in excursion propensity unrelated to instantaneous penetration.

3. RESULTS

Across the eight systems and 2016-2023, average annual vRE penetration ranged from 9% to 61% and annual curtailment of available vRE energy ranged from under 1% to 34% (Table 1). Pooled system-year regression found curtailment increasing only weakly with penetration below an estimated breakpoint of 31% average annual penetration (slope 0.14 percentage points of curtailment per percentage point of penetration, 95% CI 0.02-0.26), but far more steeply above it (slope 0.71, 95% CI 0.54-0.88), consistent with curtailment becoming the operator's primary tool for managing periods of very high instantaneous output once average penetration moves well above the roughly one-third level at which minimum synchronous-plant loading constraints begin to bind routinely.

Table 1. Summary characteristics and 2016-2023 average outcomes for the eight island power systems studied.

System	Peak demand (MW)	Avg. annual vRE penetration	Storage (% of peak)	Annual curtailment	Sustainable penetration ceiling
A	8	9%	0%	0.6%	38%
B	22	24%	0%	4.1%	44%
C	35	28%	6% (PHS)	11%	41%
D	18	33%	9%	13%	52%
E	48	39%	18%	9%	74%
F	6	45%	22%	14%	81%
G	60	52%	12% (synthetic inertia)	26%	81%
H	210	61%	17%	34%	86%

vRE: variable renewable energy (wind plus solar). PHS: pumped-hydro storage; otherwise storage is battery energy storage. Sustainable penetration ceiling is the highest instantaneous vRE penetration sustained for at least 30 minutes without a frequency excursion, averaged across 2016-2023 quarterly estimates.

Frequency excursion incidence rose sharply with instantaneous vRE penetration band. Relative to intervals with instantaneous penetration below 40%, the negative binomial model estimated 1.8 times more excursions per hour in the 40-55% band, 2.6 times more in the 55-65% band, and 4.3 times more above 65% (all $p < 0.01$ relative to the reference band), a pattern broadly consistent across systems despite substantial differences in absolute excursion rates, which ranged

from 0.3 to 6.8 events per 1000 operating hours at low penetration alone, reflecting underlying differences in load variability and thermal plant flexibility that Table 1 partly captures through peak demand and storage columns.

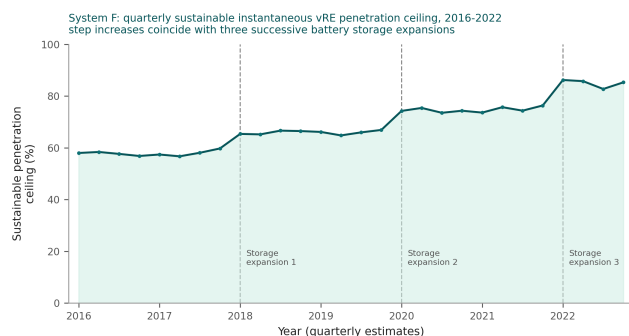


Figure 1. Quarterly sustainable instantaneous renewable energy penetration ceiling at System F, 2016-2022, showing step increases coincident with three successive battery storage capacity expansions.

The three systems with battery storage power exceeding 15% of peak demand and a frequency-responsive fast-reserve control mode (Systems E, F and H in Table 1) sustained materially higher penetration ceilings than the five without comparable storage: median quarterly sustainable penetration ceiling was 78% at the three storage-equipped systems versus 46% at the remaining five, and Figure 1 shows the ceiling at the highest-penetration storage-equipped system rising from 58% in 2016 to 86% by 2022 as battery capacity was expanded in three discrete stages, each visible as a step change in the quarterly ceiling series. At the two systems with pumped-hydro storage instead of batteries, sustainable ceilings were intermediate (58% and 64%), consistent with pumped hydro's slower ramp response constraining its contribution to sub-minute frequency support relative to batteries even where its energy capacity is considerably larger.

Table 2. Frequency excursion incidence by instantaneous vRE penetration band, pooled across all eight systems (2016-2023).

Instantaneous vRE penetration band	Operating hours	Excursion events per 1000 hours	Relative rate (vs. <40% band)
Below 40%	224,600	1.4	1.0 (reference)
40-55%	96,300	2.5	1.8
55-65%	41,800	3.6	2.6
Above 65%	27,900	6.0	4.3

Under-frequency load-shedding events were rare in absolute terms (61 events across all systems and years) but were four times more frequent, on a per-operating-hour basis, at the two systems lacking any storage or synthetic inertia provision than at the six systems with at least one such asset, and five of the six most severe events (frequency nadir below 47.5 Hz on a 50 Hz system, or the equivalent 57.0 Hz on a 60 Hz system) occurred during periods of instantaneous vRE penetration above 70% coincident with the unplanned

trip of a single large synchronous generator, indicating that high-penetration operation materially reduces the system's margin against contingencies that would have been comfortably absorbed at lower penetration.

4. DISCUSSION

These results support a central claim of the island power systems literature, that variable renewable integration on small isolated grids is constrained less by resource availability than by the operational engineering needed to maintain frequency stability and absorb energy surpluses [7,9,17], while adding cross-system quantitative evidence for two more specific points. First, the roughly 31% average-penetration breakpoint at which curtailment accelerates is broadly consistent with the level at which minimum synchronous-generator loading requirements, driven by the need to keep sufficient inertia and reserve online, begin to bind during high-output periods on systems without significant storage, a mechanism described qualitatively in earlier single-island studies [11,13] that this analysis quantifies across a multi-system sample. Second, the roughly 30-percentage-point higher sustainable penetration ceiling observed at storage-equipped systems is consistent with, and somewhat larger than, ceilings reported in prior single-system storage-sizing studies [14,18], suggesting that fast-responding storage's contribution to sustainable penetration may compound across multiple storage additions in ways that single-installation studies do not capture.

The divergence between curtailment and frequency-stability outcomes at Systems C and G is, in our view, the more practically important finding. Renewable energy targets expressed as an annual percentage of supply conflate two distinct engineering problems that require different solutions: curtailment reflects an energy balance and dispatchability problem, addressed by energy-duration storage, demand flexibility, or excess generation capacity with sacrificed output, while frequency instability reflects a power and inertia problem, addressed by fast-responding storage, synchronous condensers, or grid-forming inverter control. A system that invests in one without the other, as System G's power-focused storage illustrates, can achieve a high sustainable instantaneous penetration ceiling while still curtailing substantial annual energy, or conversely achieve low curtailment while remaining vulnerable to frequency excursions, and planners setting a single percentage target risk under-specifying which of these two investments their system actually needs.

The excess of severe under-frequency events coincident with generator trips during high-penetration periods echoes established power-system engineering concerns about reduced contingency margins as synchronous inertia declines [8,10,19], and reinforces that island systems approaching very high instantaneous renewable shares need N-1 contingency planning that explicitly accounts for the reduced inertia available at the moment

a credible contingency occurs, rather than relying on average or typical inertia levels. Several of the systems studied here have since introduced minimum online-inertia rules or synthetic inertia requirements for new wind and solar interconnections in direct response to events of this kind, a regulatory response consistent with recommendations elsewhere in the literature [9,20]. This study has several limitations. First, our eight-system sample, while spanning a useful range of size and configuration, remains small relative to the diversity of island power systems worldwide, and systems in our sample skew toward those with relatively good data availability and, plausibly, relatively more mature grid operations; systems with weaker operational data infrastructure, which may also correlate with weaker reliability outcomes, are likely underrepresented. Second, our inertia estimates rely on manufacturer-published generator parameters and treat synthetic inertia contributions from grid-forming inverters as indicative rather than independently field-verified, so absolute inertia figures should be treated with caution even where relative comparisons across penetration bands are likely robust. Third, curtailment at three of the eight systems was estimated rather than directly reported, introducing an uncertainty we bounded but did not eliminate at roughly 2 percentage points of annual vRE energy. Finally, this analysis is observational: systems were not randomly assigned their storage configurations, and unobserved factors such as operator dispatch philosophy or local grid code requirements plausibly influence both storage investment decisions and reliability outcomes, so the storage-ceiling relationship we report should be interpreted as a strong association rather than as an isolated causal effect of storage capacity alone.

5. CONCLUSION

Analysis of eight island power systems over 2016–2023 shows that curtailment of variable renewable energy accelerates sharply once average annual penetration exceeds roughly 31%, and that frequency excursions become markedly more frequent as instantaneous penetration rises above 65%, but that systems pairing high renewable shares with fast-responding storage exceeding 15% of peak demand sustained substantially higher instantaneous penetration ceilings, around 78% versus 46% at a median, than systems without comparable storage. Curtailment and frequency-stability outcomes were only loosely correlated across systems, reflecting that they arise from distinct binding constraints, energy balance and system inertia respectively, that require different technical solutions. These findings suggest that island renewable energy targets are best specified, and planned for, in terms of the storage duration, power capacity, and inertia provision needed to reach them reliably, rather than as an annual percentage share alone.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

H.S. conceived and supervised the study, negotiated the utility data-sharing agreements, and led the writing of the manuscript. C.A. processed the frequency and dispatch records, developed the inertia and penetration-ceiling estimation methodology, and performed the statistical analysis. R.G. compiled and cross-validated the curtailment and storage configuration data and produced the figures and tables. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only operational frequency, dispatch, and curtailment records obtained from utility and system operator sources under research data-sharing agreements, and publicly available system specifications, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Operational frequency and dispatch data used in this study were provided by the respective island utilities and system operators under data-sharing agreements that do not permit public redistribution of the raw records. Aggregated system-year statistics, processed penetration-ceiling series, and analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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