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# An investigation into the effects of high renewable energy penetration in the Pacific Islands: A case study of Niue

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**Abstract**
The transition from diesel-dependent isolated grids to hybrid renewable energy systems presents both technical opportunities and operational challenges for Pacific Small Island Developing States (SIDS). This study presents a quasi-dynamic simulation analysis of Niue's power grid under five progressive renewable energy integration scenarios, modelled using DIgSILENT PowerFactory. While the existing network infrastructure is demonstrated to be adequate for all modelled transition scenarios, the progressive introduction of variable renewable energy sources fundamentally alters grid behaviour, shifting from stable and predictable diesel dispatch to an increasingly dynamic system. The study identifies that Battery Energy Storage Systems (BESS) are critical enablers of diesel displacement, but their effectiveness is highly sensitive to PV system sizing and diesel operational practices. Prolonged low-loading of diesel generators under high renewable penetration is shown to pose risks of wet stacking with direct implications for asset management in small island utilities. The imposition of a minimum diesel loading constraint, while necessary for generator health and frequency stability, is found to saturate storage capacity and necessitate renewable curtailment, highlighting a fundamental tension in hybrid system operation. Additionally, the progressive reduction of synchronous generation raises considerations regarding grid inertia that warrant dedicated frequency stability investigation. The findings offer transferable insights for renewable transition planning across Pacific SIDS with similar isolated grid contexts.

*Keywords*: Grid stability study; High renewable energy penetration; Quasi-dynamic simulations.

## 1. Introduction

Pacific Small Island Developing States (PSIDS) face a distinct and persistent energy challenge. Their electricity systems are small, geographically isolated, and entirely self-contained, with no access to regional transmission networks or neighbouring grid support. As a result, most Pacific Island communities have historically depended on imported diesel fuel as their primary source of electricity generation (Succetti et al., 2023; Wang et al., 2024). While diesel generators (DGs) offer the operational simplicity and dispatchability that these small island grids require, this dependence comes at a considerable cost, driven by the price of imported fuel and the logistical burden of long ocean supply chains. The associated fiscal pressure on island governments, combined with the vulnerability of isolated economies to oil price volatility and fuel supply disruptions, makes energy security a pressing concern across the region (Filho et al., 2022).

In response, Pacific Island nations have increasingly committed to ambitious renewable energy targets (Asian Development Bank, 2022). The potential benefits are significant: displacing diesel with renewable energy offers lower electricity costs, reduced fuel import expenditure, improved energy independence, and meaningful reductions in greenhouse gas (GHG) emissions, a matter of particular importance given that Pacific Island communities are among the most acutely vulnerable to the impacts of climate change (Ocon & Bertheau, 2019). Regional frameworks supported by IRENA, the Pacific Community, and bilateral development partners such as the Ministry of Foreign Affairs and Trade have accelerated investment in solar photovoltaic (PV) and battery energy storage systems (BESS), with many island nations now pursuing renewable energy (RE) targets of 80% or above (Government of Niue, 2015; Ministry of Foreign Affairs and Trade, 2025).

Arévalo et al. (2025) describes that despite the compelling case for RE integration, the technical challenges it introduces into small island grids are substantial. Conventional DGs provide more than just energy. Their rotating machinery contributes synchronous inertia, which resists sudden frequency deviations, and reactive power support, which stabilises voltage (Asian Development Bank, 2022). As solar PV progressively displaces diesel generation, total system inertia declines, and the grid transitions towards a low-inertia state. In low-inertia systems, the rate of change of frequency (RoCoF) following a generation-load imbalance increases significantly, leaving less time for protective relays and governing systems to respond, making the grid more sensitive to disturbance (Mangunkusumo et al. 2025). Small island systems are especially susceptible to these effects: their low total generation capacity means that even minor imbalances can cause rapid and severe frequency disturbance, and the absence of interconnection with external networks removes any stabilising inflow of power that a larger grid would otherwise provide (Succetti et al., 2023).

Beyond frequency, the displacement of synchronous DGs by inverter-based generation introduces significant voltage stability concerns (Mangunkusumo et al., 2025). Synchronous machines inherently supply reactive power to the network, actively supporting voltage levels under varying load conditions. Inverter-based generation, by contrast, does not naturally provide this reactive support unless explicitly configured to do so. As diesel units are taken offline, the loss of their reactive power contribution can render the network susceptible to voltage instability (Ochoa-Correa et al., 2025). In weakly meshed distribution networks, these voltage fluctuations are amplified, as the network has limited capacity to redistribute reactive power or dampen transient disturbances across alternative paths.

The intermittent nature of solar generation further compounds these challenges through its impact on power quality. Overcasts and the diurnal variability of the solar resource introduce rapid fluctuations in real power output that propagate through the network as voltage variations and harmonic distortion (Liang, 2017). In small island grids with limited generation diversity and high renewable shares, these power quality issues are difficult to suppress through grid impedance alone and may require dedicated mitigation measures. Poor power quality not only affects the performance and longevity of sensitive electrical equipment but can also interfere with the protective relay systems on which grid stability depends. At high RE penetration levels, the minimum loading constraints of diesel units, which may need to stay online to provide stability can also begin to limit how much solar energy the grid can utilize (Lucas et al., 2017).

The experience of Niue, a self-governing Pacific Island nation with a population of approximately 1,700 people, illustrates this challenge directly (Niue Statistics Office, 2022). Niue's electricity system is a small, isolated grid historically powered by imported diesel, with an installed generating capacity of around 2 MW (Government of Niue, 2024). The island has adopted a target of 80% renewable electricity under its Strategic Energy Road Map (NiSERM) 2015-2025, with solar PV as the primary renewable resource (Government of Niue, 2015). However, early attempts to integrate solar generation encountered significant stability problems. In 2014, grid instability forced a portion of the island's solar capacity to be taken offline, highlighting the concern of increasing renewable penetration while maintaining system stability. Nevertheless, the path towards significantly higher penetration and the stability implications of that transition remains technically unresolved. Niue therefore represents both a timely and highly instructive case study: its grid is small and well-defined, its renewable energy trajectory is well-documented, and the stability challenges it has already encountered make it an ideal setting in which to rigorously examine the limits of renewable integration in a small island power system.

### 1.1. Objectives of the paper

This paper investigates the impact of increasing renewable energy penetration on grid stability in the Niue power system. Using the PowerFactory software of DIgSILENT (2026), a detailed model of the Niue grid was developed and used to simulate system behaviour — including frequency response, voltage regulation, and system inertia — under a range of solar PV penetration scenarios. The extent to which diesel generation can be offset within the bounds of acceptable grid stability is treated as a secondary but related outcome of the analysis. The specific objectives are to:

- Establish a representative power system model of the Niue electricity grid in DIgSILENT PowerFactory, incorporating current generation assets, network topology, and load characteristics.
- Simulate grid performance under increasing levels of solar PV penetration, assessing the impact on voltage stability across a defined range of scenarios.
- Identify the stability limits of the Niue grid under high renewable penetration and quantify the degree to which diesel generation can be feasibly offset within those limits.
- Provide technically grounded insights that can inform future renewable energy planning and grid investment decisions for Niue and comparable small island power systems across the Pacific region.

## 2. Literature review

The literature review examines recent developments in island grids with increasing variable renewable energy sources (VRES) penetration. It focuses on techno-economic grid effects and strategies to overcome operational barriers, specifically investigating the following key questions:

- How do low-inertia island grids perform with increasing penetration of VRES?
- What are the most effective technologies to mitigate grid-stability challenges associated with increased VRES penetration?

### 2.1. Review approach

To identify what is deemed as important to researchers concerning the integration of VRES into isolated grids, a narrative literature review was undertaken. Narrative reviews facilitate the inclusion of a diverse range of studies that might otherwise be excluded by the rigid criteria of a systematic review. This approach is useful for exploring topics where foundational knowledge is still limited, allowing for broader conceptual insights (Sarkar & Bhatia 2021).

The scope of this review is confined to the technical and physical aspects of grid integration and its effects. Consequently, articles that focus on policy frameworks, socio-economic drivers, and the logistical scale of infrastructure implementation were not considered. Through the use of predefined search queries and keywords, the review process involved the utilization of multiple academic databases. The literature was restricted to articles published from 2017 onwards to ensure the inclusion of recent findings.

Following the initial literature search, the identified articles underwent a preliminary screening of their abstracts to determine relevance. Irrelevant papers were excluded, while the remaining literature was subjected to a comprehensive content analysis. During this process, recurring themes and methodological approaches were documented. Finally, the review identified the critical areas of research required to support the successful integration of VRES into existing island grids.

### 2.2. Review outcome

Thirty articles were included in the review.

#### 2.2.1. Temporal and geographic development

The earliest research focused on identifying the fundamental vulnerabilities of isolated power systems. Kumar et al. (2017) demonstrated that sudden variations with PV generation in systems like Kiribati lead to immediate voltage and frequency instability during periods of low demand. This initial period centred on defining the ceiling for RE penetration, with Lucas et al. (2017) and Michalena & Hills (2018) concluding that weak Pacific island grids often hit stability limits at penetration levels as low as 26–30%. While these studies identified the risks, Liang (2017) and early reviewers began suggesting control-technology-based solutions, specifically the Virtual Synchronous Machine (VSM), to emulate the mechanical inertia of traditional generators to improve power quality.

Building on this diagnostic foundation, the literature shifted toward the implementation of specific technical requirements for hybrid systems. Hamilton et al. (2019) provided critical evidence from Australian isolated communities, concluding that low-load diesel generation and demand-side management (DSM) could act as "synthetic storage," reducing the immediate need for expensive BESS. Concurrently, Prasad & Raturi (2019) noted that reaching higher penetration in regions like Fiji requires moving beyond simple solar integration toward grid storage options capable of managing instantaneous generation output changes. This period also saw practical milestones, such as Rojas et al. (2020) documenting the use of BESS with grid-forming inverters on St. Eustatius island to successfully serve as a primary voltage source, allowing DGs to be deactivated for up to 11 hours daily.

As the field progressed into the early 2020s, research increasingly concentrated on sophisticated control schemes and systematic transition metrics. Tan et al. (2022) proposed synergistic balancing control for low-inertia systems, demonstrating that PV stations can function as dispatched regulating units via automatic generation control (AGC). This transition was marked by a deeper understanding of Rate of Change of

Frequency (RoCoF), which Homan et al. (2021) identified as a critical metric that only becomes unmanageable when inertia levels drop below 20%, requiring fast-acting frequency response (FR). Filho et al. (2022) reinforced the link between RE and energy security in SIDS, concluding that BESS offers a more stable alternative to diesel-dependent security models. Extending this further, Khan et al. (2023) advocated for energy storage devices to provide robust damping of frequency oscillations through optimised Load Frequency Control (LFC) and virtual inertia provisio, while Succetti et al. (2023) highlighted that island grids require not only storage, but sophisticated deep learning forecasting to balance stochastic resources.

The most recent literature, the focus has shifted toward high-fidelity stability design and the pursuit of purely zero-carbon microgrids. Psarros et al. (2024) identified that storage as an absolute prerequisite for exceeding 50% RE penetration, classifying centrally managed stations and hybrid plants as the primary architectures for system flexibility. Ducoin et al. (2024) refined this by developing analytical designs for grid-forming and grid-following inverters, ensuring stable frequency trajectories across all grid buses. Akram et al. (2024) proposed a novel P-Q-FFR reserve method that modulates active and reactive power injection to enhance short-term stability more cost-effectively than conventional FFR reserves.

The most recent studies extend this trajectory toward full decarbonisation and adaptive system intelligence. Astapov et al. (2025), advocate for a three-layered implementation framework to address voltage fluctuations through real-time adaptive inverter controls, while Figueredo et al. (2025) demonstrated that isolated zero-carbon microgrids can meet full annual load demand autonomously by combining multiple renewable sources with long-duration storage like hydrogen and battery storage. In parallel, research into asset repurposing by Mangunkusumo et al. (2025) and Jiang et al. (2026) introduced a "dedieselization" strategy that converts retired DGs into synchronous condensers (SCs) to restore lost mechanical inertia and system strength. Complementing this, Njoka et al. (2025) using frequency sensitivity analysis to determine the precise bus locations where BESS can most effectively enhance frequency nadir and reduce RoCoF. Finally, Ghalib et al. (2025) and Liaqat et al. (2026) advocate for adaptive AI controllers and hierarchical machine learning to manage the complex, non-linear dynamics and protection challenges inherent in 100% renewable microgrids.

#### 2.2.2. Pacific island context

A distinct and growing body of literature specifically focuses on Pacific islands as subject studies, identifying unique regional constraints. Beyond the early work in Kiribati and Fiji, Matragi et al. (2025) used the Tahitian grid to show that simplified generator models significantly underestimate instability risks, finding that integrating BESS as a spinning reserve is essential for handling N-1 contingencies, such as the loss of a major diesel unit. Arifin et al. (2025) further highlighted the role of hybrid plants in reducing diesel fuel consumption in similar island contexts. Finally, Pueyo & Haas (2025) emphasized that while 100% RE systems are technically feasible in the Pacific, their success depends on moving away from donor-dependent models toward stable regulatory frameworks that attract private investment for dispatchable renewable solutions like coconut oil generators and BESS.

### 2.3. Review discussion

The literature identifies that grid stability is now recognized as the primary challenge for successful energy transitions, as dependency on VRES grows. Storage solutions are a major focus in nearly a third of recent research, highlighting their role as a required foundation for reaching high levels of clean energy. While early studies viewed RE integration as a general problem, more recent work focuses on the specific behaviour of inverter-based systems. There is an increasing emphasis on moving beyond simple energy balancing toward understanding high-fidelity grid responses, utilizing methods such as smart-grid optimization and demand-side management to maintain system integrity.

A recurring theme is the vulnerability of low-inertia grids. There is a clear consensus that as synchronous generators are retired, system reliability naturally declines due to the loss of mechanical inertia, leading to increased frequency volatility and faster rates of change. Despite this consensus, a gap remains: current research often focuses on single islands rather than providing a broad comparison of how different small grids behave as renewable levels increase.

In terms of solutions, the focus has moved from single technologies to hybrid strategies. Grid-forming technology and the repurposing of retired assets into synchronous condensers are emerging as essential tools for restoring system strength and providing the "virtual inertia" necessary for stability. Furthermore, the rise of AI-driven management using deep learning for forecasting and adaptive controllers for fault detections are making grids more proactive.

However, there is still not enough research specifically for standalone microgrids on small islands. Most island-focused studies are approached from a techno-economic or cost-benefit perspective, often neglecting the precise operational stability limits of these isolated systems. While snapshots of individual islands like Fiji or Kiribati exist, there is a lack of high-fidelity modelling that determines the absolute "glass ceiling" for renewable penetration in small-scale environments. This absence of research on how to make these specific microgrids both flexible and reliable represents a significant opportunity for future case studies, as many islands face unique geographical and environmental constraints that cannot be addressed by larger grid models.

## 3. Research methods

The research revolved around modelling the grid of the island nation of Niue (see Figure 1). Operated by the Department of Utilities, the Niue Power Corporation (NPC) manages an 11 kV underground ring main that services the entire island. This network supports 720 residential, 50 commercial, and 90 government customers, powered by a central station housing two DGs (one in-service and one standby). Furthermore, various distributed solar PV installations exist throughout the island but are currently disconnected, awaiting technical inspection and reintegration into the grid.

The grid used in this project is intended to be as realistic as possible. To ensure this, the following data were collected through site-visits and discussions with grid experts at the NPC to create a base case:

- The capacity and location of existing generators;
- Node connections and locations;
- Transformer ratings and other parameters;
- Base voltage level;
- Frequency; and
- Load profiles.

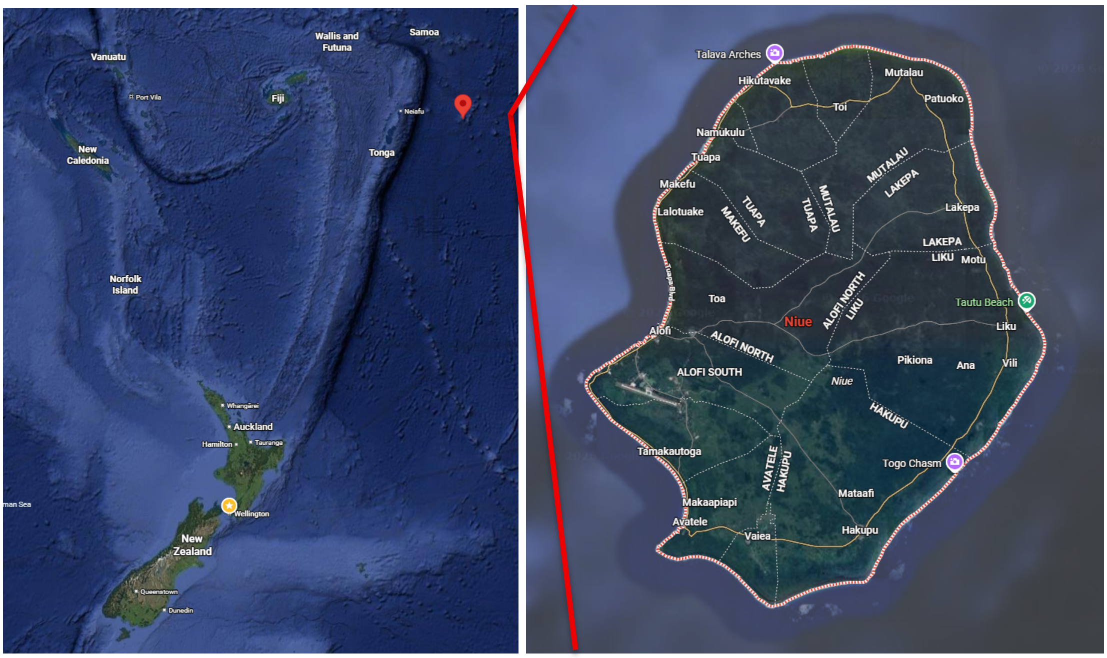


**Figure 1. Location and map of the Island Nation of Niue**

The PowerFactory software of DIgSILENT was used to model the grid and carry out the simulations. PowerFactory is a leading power system analysis software application for use in analysing generation, transmission, distribution and industrial systems. Relevant features for this research include:

- Models of generators and governors (steam, gas, diesel, hydro);
- Models of BESS (type 2 power measurement controller);
- Steady-state load flow calculations taking into account voltage-dependent reactive power capability limits, and so forth;
- PV system model with integrated power calculation based on solar radiation (1 and 3-phase technology); and
- Medium- to long-term user-defined modelling for quasi-dynamic simulation (QDS).

Given its expansive list of capabilities, it was seen as the optimum choice for modelling the grid for this research.

Niue has two feeders (North and South) which were modelled in detail. The modelling entailed:

- Modelling line lengths, types, material and locations;
- Ensuring the transformer parameters and locations match current real world; and
- Using the load profiles provided by the utility.

The load information received from NPC consisted of the total load for each generator in one-hour blocks. The load information for every hour was extracted to create a one-year load profile. The distribution network has 68 pad-mounted transformers of capacities ranging from 15kVA to 1000kVA. A total of 68 loads were modelled, where the distribution of the load's magnitude was calculated from transformer nameplate capacities, normalised in relation to the power draw of the associated feeder.

The power station houses two generators (in-service and backup) rated at 1 MW. While the station also features a 262.4 kWp ground-mounted PV system and two Tesla BESS units with a combined capacity of 3.15 MWh, both the solar and storage assets are currently disconnected from the grid. Similarly, approximately 820 kW of distributed solar capacity across the island remains offline. To account for future expansion, the model includes the 2026 MFAT renewables project, comprising 2.79 MWp of PV and a 1.98 MW/8.19 MWh BESS. PV systems and BESS models were directly referenced from nameplates and available literature provided by NPC. Further specifications are listed in Table 1.

**Table 1. Niue distributed PV and BESS**

| Location | Capacity $kW_p$ | Inverter Capacity kW |
|---|---|---|
| Fish Factory | 40 | 40 |
| Primary School | 20 | 20 |
| Hospital Rooftop | 37 | 40 |
| Hospital Ground | 600 | 525 |
| Public Works | 20 | 20 |
| Water Works | 12 | 20 |
| MFAT PV | 2,790 | 2,310 |
| MFAT BESS | | 1,980 |

The powerhouse is serviced by two station transformers that step up the voltage from 415V to 11kV for transmission around the island. The distribution transformers step the voltage back down to 415V for distribution to customers. The specifications of the pad-mounted and station transformers were not received from NPC, so they were modelled after typical ETEL branded transformers that are used in Aotearoa New Zealand using the capacities stated on the single line diagram.

Exact line lengths, types, and the locations of the pad-mounted transformers were also not received from NPC. The locations of the transformers were obtained by referencing the single line diagram and having field personnel trace the island until transformers were found. All locations were recorded. Once the locations were input into PowerFactory, the line lengths between objects were automatically calculated. For line type, it was determined that the lines were single-core Aluminium Cross-Linked Polyethylene (XLPE) with nominal area of 50 sq. mm. All investigative changes were done on the detailed feeders, and the behaviour of the overall system observed.

### 3.1. Simulation

Buses are nodes where one or more components (generators, loads, transformers, and so forth) are connected. There are three types, but of great importance to carrying out a successful simulation in PowerFactory is the Slack (SL) Bus. This is also known as the Reference Bus and is designed to balance the active and reactive power in the system due to system losses. The slack bus provides the reference for the phase angles and absorbs the discrepancy in power flow calculations, adjusting to balance load and generation across the system. Total generation should be equal to (total load + transmission losses). However, these losses cannot be directly calculated until the load flow is solved. The SL bus provides the necessary balance by adjusting its real power to match system losses. There is one SL bus in a system, and it is often linked to the main control point of a large utility.

For Niue, there is one power plant that houses the generators. Consequently, the bus that the generators are connected to is the only one that can be designated as the SL bus. Generator "PH Gen1" was designated as the reference machine. This means that the generator is configured as slack. The implications of this are that the voltage angle of whatever terminal the generator is attached to is fixed, and that balances active power if the Active Power Control option as Dispatched is selected and the Balancing option by Reference Machine is enabled.

Analysis of the power station logs identifies April as the month of peak demand, with July experiencing the lowest. Consequently, the system was modelled for these two months to establish performance benchmarks under normal operating conditions. A QDS was then performed for these months to establish the baseline values for the following parameters:

- Terminal voltages (p.u.);
- Line losses (kW);
- Line loading (%);
- Transformer loading (%)
- Generator loading (%);
- Generator active power (kW); and
- Battery SOC.

The grid was analysed across five distinct scenarios to evaluate system behaviour and quantify the potential cost savings from reduced diesel dependency. Case 1 establishes a baseline where demand is met solely by diesel generation, while Case 2 assesses the contribution of reconnecting existing PV assets. Case 3 examines the operational impact of integrating the existing powerhouse BESS alongside these active PV assets. Meanwhile, Case 4 explores system performance following the integration of the new MFAT assets. Finally, Case 5 explores full system expansion performance while maintaining a healthy generator loading operation. These scenarios are summarized in Table 2.

**Table 2. Grid study case scenarios**

| No. | Case scenarios | PV Online | BESS Online | Description |
|---|---|---|---|---|
| 1 | Baseline generation | No | No | Establishes the current operational baseline where the nation's demand is met exclusively by diesel generation. |
| 2 | Distributed PV integration | Yes | No | Evaluates grid performance following the re-energization of existing powerhouse and distributed PV assets alongside diesel generation. |
| 3 | Existing BESS integration | Yes | Yes | Assesses the combined impact of active PV assets and the re-energized powerhouse BESS on system stability and diesel displacement. |
| 4 | Full system expansion | Yes | Yes | Explores the complete grid configuration, including all existing assets and the integration of the new MFAT PV and BESS capacity. |
| 5 | Full system expansion with 30% minimum DG loading | Yes | Yes | Explores the full system expansion with minimum stable diesel limitation of 30% generator loading |

With each scenario:

- Power flow studies were carried out to see how the flows changed as more solar PV is injected into the grid;
- Battery states of charge (SOC) were observed;
- Voltage stability was assessed with the incremental increase of solar PV; and

- Change in grid losses with increasing solar PV was investigated.

Plots were generated for all the parameters checked, as visual indicators of the result. The data was exported to CSV files for further analysis.

### 3.2. Modelling assumptions

While all care was taken to minimise the assumptions required in the model, the following assumptions were made:

- As the model created for this study focused primarily on steady-state operation of the power system, detailed models of the protection systems were not considered.
- Distribution transformer loadings were assumed to be 100% as actual measurements were unavailable for cross-validation.
- The static load flow model was not validated against real word measurements, only assessed for reasonableness.
- The station voltage controller ultimately controls the import and export of reactive power within the power station. The exact scheme utilised by the generators in the power station was unknown, so a station voltage controller, responding to voltage fluctuations at the power station bus, was implemented.
- The exact active power dispatch scheme in the power station was also unknown, so an active power controller was developed for the model. The dispatch scheme assigns a priority to the generator and BESS, known as merit order, which determines the order each equipment enabled/disabled to meet demand.
- The exact workings of the BESS controller were also unknown. A type 2 power measurement controller from the PowerFactory library was customised for the application. It monitors the input/output power of the PV bus system, and limits can be set in order to determine the charge/discharge rates, the start/stop power magnitudes to begin charging/discharging, min and max state of charge (SoC) as well as the initial SoC. The variables were carefully tuned to ensure minimal PV curtailment.
- The built-in capability of PowerFactory would be used for building the irradiance and temperature profiles of the locations.

## 4. Results and discussion

This section presents and evaluates the simulation results for Niue's power system based on the parameters established in section 3.1. The analysis compares the grid's performance across various renewable energy (RE) expansion scenarios. To contextualize these findings, Figure 2 illustrates the PowerFactory grid model network topology, where the North and South feeders are highlighted in blue and red, respectively, and the central powerhouse components are indicated in purple.

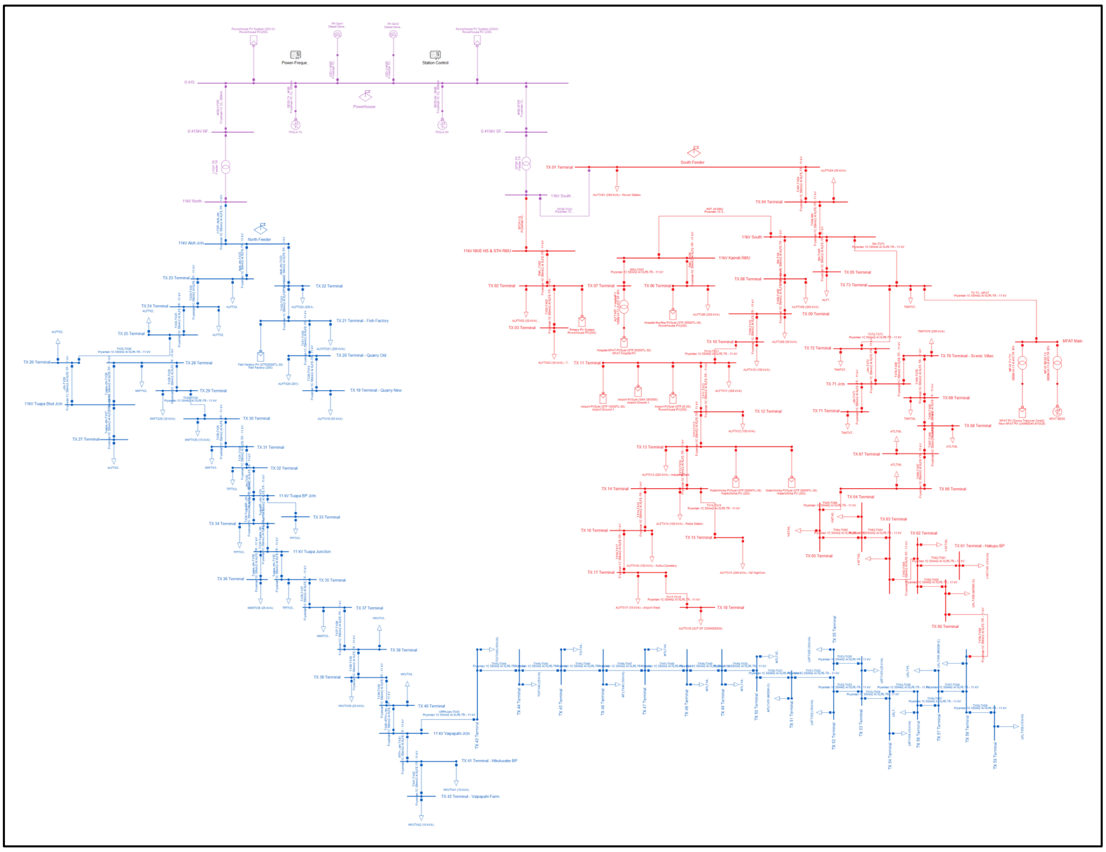

**Figure 2. Niue network single line diagram**

### 4.1. System modelling results

The baseline simulation models the existing components and historical operation of the Niue grid. The resulting month-long data serves as the reference case against which all subsequent integration scenarios are compared. Key network performance indicators are summarized in Table 3.

**Table 3. Results of parameters in base case**

| Parameter | April | July |
|---|---|---|
| Transformer Loading (Max) | 48.21% (south feeder TR) | ~44% (south feeder TR) |
| Line Loading (Max) | 23.64% | 21.55% |
| Line Losses (Max) | 1.05 kW | 0.821 kW |
| Terminal Voltage (Min) | 0.9966 | 0.9993 |
| Terminal Voltage (Max) | 1.008 p.u. | 1.012 p.u. |
| Total Energy Generated | 431,495.6279 kWh | 344,998.6218 kWh |

### 4.2. Case scenarios results

While simulations were conducted for both April and July, this section focuses on the July results as the lower PV generation and reduced load demand present a more conservative operating condition, where grid control challenges are still observed despite diminished renewable resource availability, suggesting these would be more pronounced during the higher generation period of April.

### 4.2.1. Terminal voltages

In power distribution, service voltages for normal operations are kept within a strict range of 0.95 p.u. to 1.05 p.u., a widely adopted standard reference from ANSI C84.1 (NREL, 2003) and applied here as a benchmark in the absence of a specific local voltage regulation standard for Niue.

Across all case scenarios, the integration of the PV and BESS assets maintained stable voltage profiles within these permissible boundaries as shown in Figure 3. The observed voltage rise can be attributed to distributed PV systems back-feeding active power throughout the grid, an effect that is further compounded by the nature of Niue's underground cable network. Underground cables inherently exhibit higher capacitance per unit length compared to overhead lines. This elevated capacitance generates leading reactive power, which amplifies voltage rise at remote nodes, particularly under light loading conditions where PV back-feeding is most pronounced (Baghban-Novin et al., 2020).

The voltage sags observed are directly linked to high-capacity BESS charging intervals. During peak solar hours, the centralised battery units draw significant current to absorb surplus PV generation, and this concentrated demand combined with the simultaneous de-loading of the primary diesel generator creates a localised voltage drop across the affected terminals.

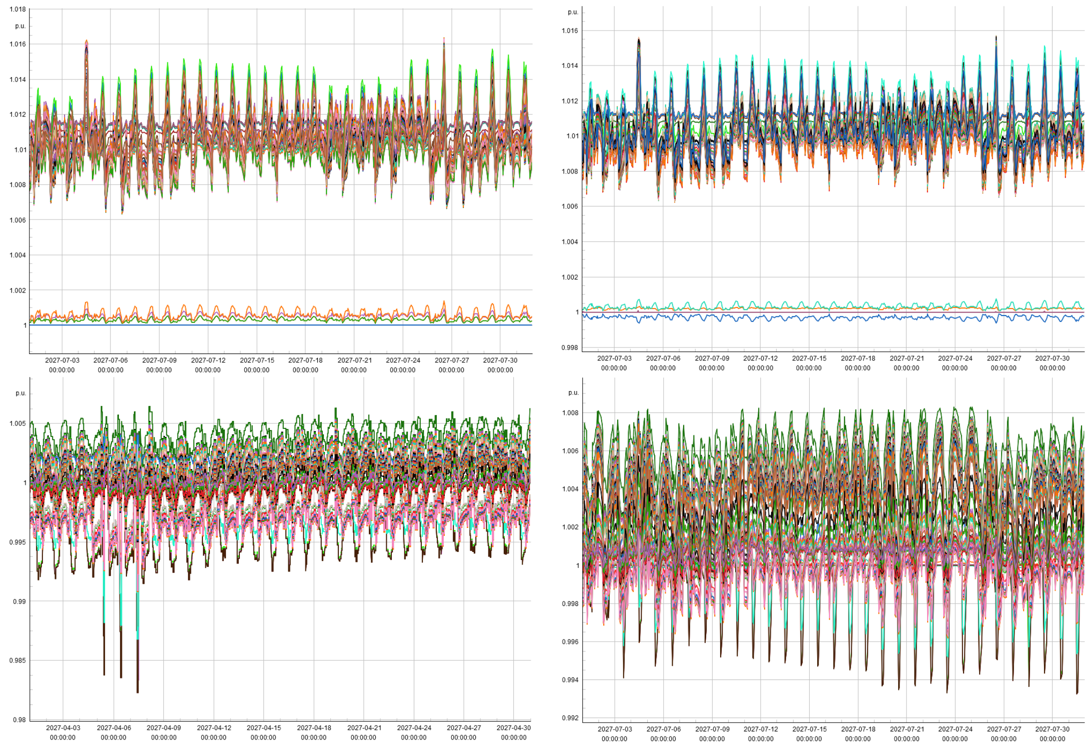

**Figure 3. Terminal voltage plots: Case 2 (top left), Case 3 (top right), Case 4 (bottom left), and Case 5 (bottom right)**

### 4.2.2. Line loading

Line loading quantifies how heavily a line is utilised relative to its current carrying capacity, where sustained overloading risks conductor overheating and safety hazards. Across all five cases, loading remained well within limits, confirming the adequacy of existing conductor infrastructure. In the base case, loading profiles are stable and predictable, reflecting the controllable nature of diesel dispatch. The progressive integration of VRES fundamentally alters this behaviour. With the introduction PV output results to intra-day oscillations that track the solar irradiance cycle, as embedded generation induces bidirectional power flows across the network. The addition of BESS further introduces localised discharge spikes on storage-connected lines. As the system expands toward full renewable capacity in Cases 4 and 5, loading profiles become increasingly more complex and irregular. Despite this growing complexity, no overloading was recorded across any scenario as shown in Figure 4.

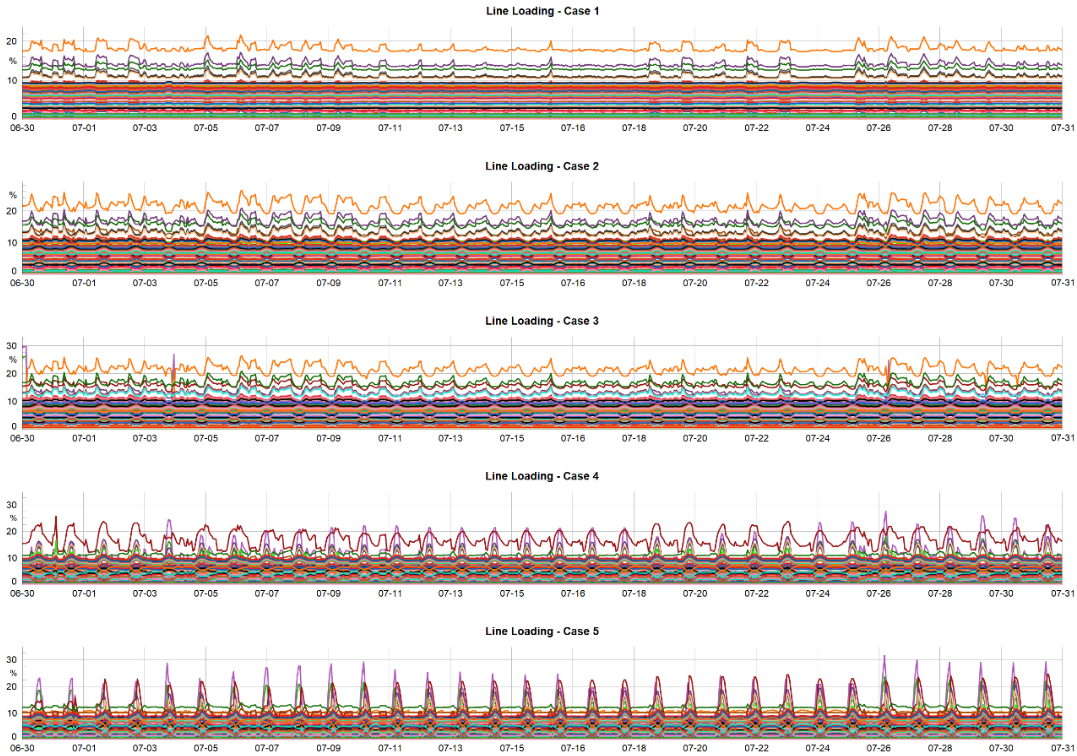


**Figure 4. Line loading across case scenarios**

### 4.2.3. Line losses

Line losses represent the electrical energy dissipated as heat through conductor resistance, governed by the relationship $P = I^2R$. As shown in Figure 5, in the base case, losses are minimal and stable. The plot reflects the predictable, unidirectional current flows characteristic of centralised diesel dispatch. The introduction of distributed PV in Case 2 produces a marginal but observable increase in losses, as embedded generation induces bidirectional current flows through lines, increasing the effective $I^2R$ burden across the network. This demonstrates that even moderate VRES penetration can incrementally erode network efficiency despite reducing diesel output. The addition of BESS in Cases 3 through 5 fundamentally changes the loss profile from a continuous low-level pattern to one dominated by sharp, isolated spikes, driven by high-magnitude discharge currents on BESS-connected lines. While these spikes are brief, their cumulative energy impact over extended operation requires consideration when evaluating the overall system efficiency.

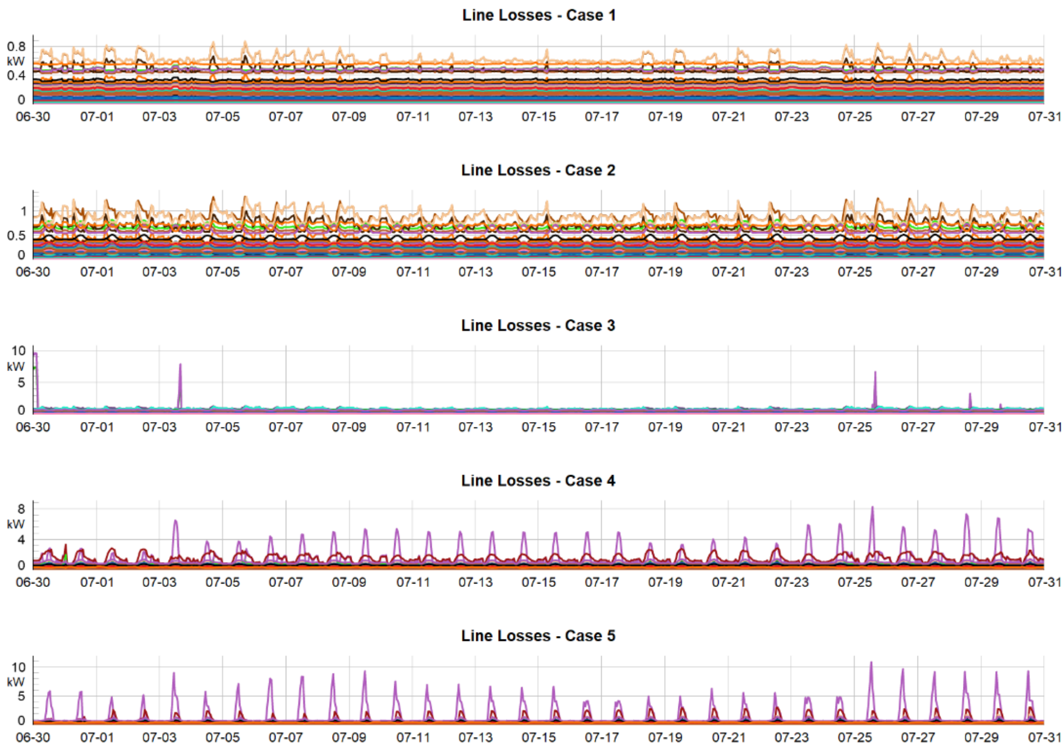


**Figure 5. Line losses across all case scenarios**

### 4.2.4. Transformer loading

Like line loading, transformer loading measures how much of a transformer's rated capacity is in use. Monitoring transformer loading is essential for preventing overloading, informing asset lifecycle planning, and ensuring transformers are appropriately sized for the power flows in their respective areas. However, this analysis is limited to power station transformers and those directly connected to PV and BESS assets, as distribution transformers serving load nodes could not be modelled due to the absence of actual spot-check data and were conservatively assumed at 100% loading.

As presented in Figure 6, in the base case, only the NFDR and SFDR power station transformers are observable, both operating steadily between 33–40% with smooth profiles consistent with centralised diesel dispatch. The introduction of PV assets in Cases 2 and 3 brings the Hospital PV transformer (ALFTX07) into operation, exhibiting a characteristic daytime-only square wave profile confirming generation-hours-only energisation, while the NFDR and SFDR transformers show a marginal increase in loading attributable to the additional power flows introduced by PV injection. The powerhouse BESS in Case 3 does not produce a visibly distinct transformer signature, as its operation is absorbed within the power station bus rather than through a separately modelled transformer, limiting direct observability in this analysis. In Cases 4 and 5, the addition of MFAT assets introduces the MFAT PV and BESS transformers, with the MFAT BESS transformer exhibiting the most dynamic behaviour, while the power station transformers experience further increased variability driven by the expanded renewable generation interacting with the network.

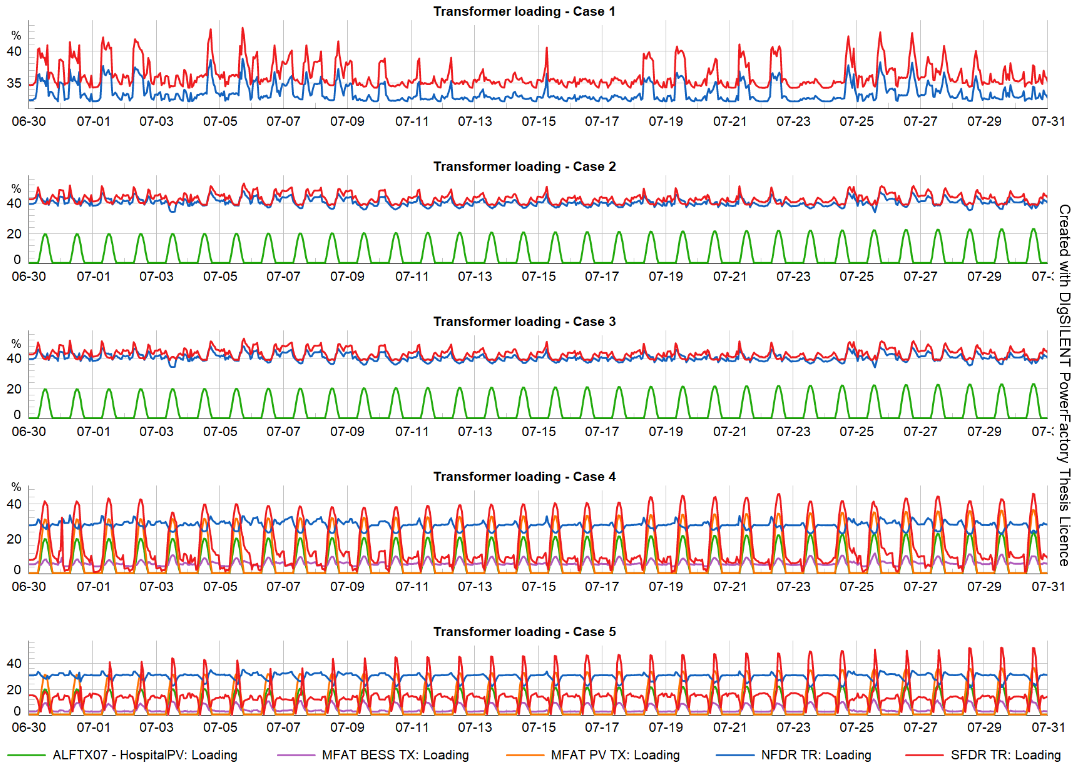


**Figure 6. Transformer loading across all case scenarios**

Throughout all cases, the SFDR transformer consistently exhibits greater variability compared to NFDR. This is attributable to the network topology where most renewable assets are connected on or near the South Feeder, meaning PV generation events, BESS discharge cycles, and reverse power flows predominantly pass through the SFDR transformer. Furthermore, given that the network operates as a meshed loop, excess generation on the South Feeder side circulates back through the network, compounding the loading variability seen at SFDR. All modelled transformers remained within operational bounds across all scenarios, though the incomplete visibility of load-side transformer behaviour represents a key limitation.

### 4.2.5. Generator loading

Generator loading reflects the degree to which a diesel generating unit is utilised relative to its rated apparent power capacity in kVA. Monitoring generator loading is critical in hybrid renewable systems, as excessive loading risks mechanical stress and reduced equipment lifespan, while prolonged underloading can cause wet stacking and combustion inefficiency in diesel engines. The generator loading was calculated using Equation 1:

$$Generator\ load\ \% = \frac{S = \sqrt{P^2 + Q^2}}{Nominal\ Rating\ (kVA)} \tag{1}$$

As PV displaces diesel active power generation, the diesel generator remains the primary voltage and frequency regulator of the grid and must continuously adjust its reactive power output to maintain system stability. Since loading is calculated from total apparent power, which combines both active and reactive components, loading can increase even as active power output decreases.

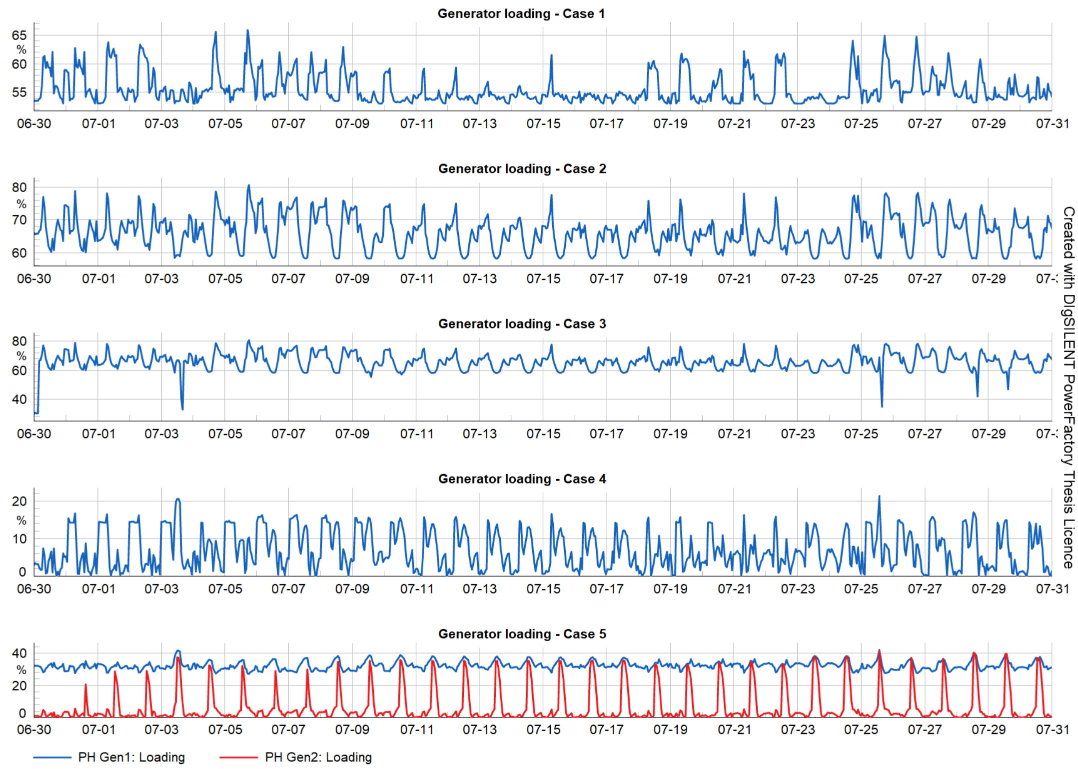


**Figure 7. Generator loading across all case scenarios**

As presented in Figure 7, in the base case, Gen 1 operates within a narrow and stable band between 55–65%, reflecting predictable diesel-only dispatch. The introduction of PV in Case 2 produces a marked increase in loading variability, with Gen 1 swinging between 55–80% as it compensates for PV intermittency while simultaneously managing reactive power demands. The addition of BESS in Case 3 partially mitigates this variability, with storage buffering PV fluctuations and reducing the frequency of rapid generator response. Case 4 represents the most significant turning point, where the full MFAT PV and BESS expansion drives Gen 1 loading down to predominantly 0–20%. While this reflects near-complete diesel displacement, sustained operation at such low loading levels is detrimental to diesel engine health due to incomplete combustion and carbon buildup, shortening engine lifespan and increasing maintenance costs. This is precisely the operational concern that motivates the minimum loading constraint imposed in Case 5, with Gen 1 holding a consistent floor at approximately 30–35%, while Gen 2 operates as the reference machine absorbing remaining system variability through periodic spikes reaching up to 40%. Collectively, these profiles illustrate a clear diesel displacement trajectory consistent with increased VRES penetration.

#### 4.2.6. Grid motoring

A potential effect of introducing VRES to the grid is that the generators absorb power from the grid instead of pushing power to it, also known as motoring. This behaviour is characterised when PV generation exceeds current demand. Motoring poses a risk to grid stability as it disrupts the fundamental balance between generation and load, and if left unmitigated, can cause frequency deviations that may trigger protective relay operations, potentially leading to generator trips and subsequent loss of supply. This was clearly observed through several instances of reverse power flow on the diesel generation plot for Case 2 in Figure 8. This motoring effect intensifies with respect to total PV system size as it increases. However, this effect can be mitigated with the introduction of BESS units in Case 3. Aside from supporting the grid during hours where there is no solar generation, the BESS units prevent motoring by absorbing excess PV generation. Moreover, modern PV inverters are capable of active power curtailment through their integrated control systems, deliberately operating below the maximum power point when instructed by the energy management system (EMS), effectively reducing PV output when neither the grid nor the BESS units can absorb the surplus.

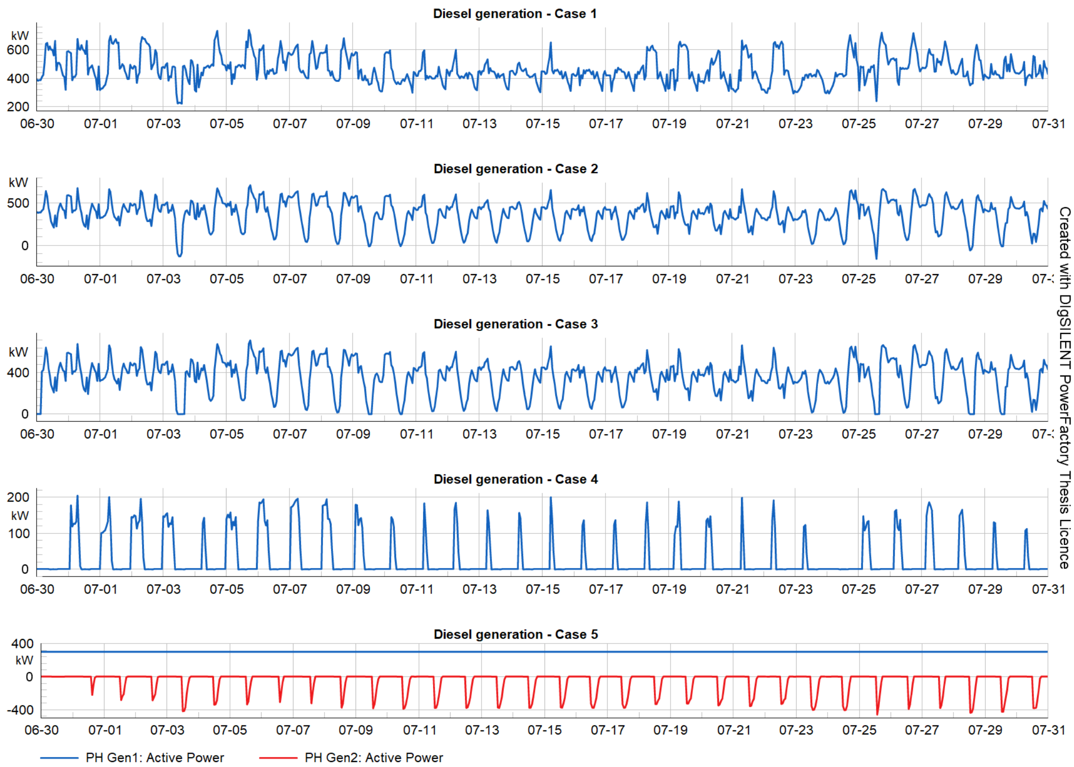


**Figure 8. Diesel generation across all case scenarios**

Beyond the motoring observations, the simulations also quantify the progressive level of diesel displacement achieved with each successive case. As the penetration of VRES increases from Cases 2 through 5, the diesel generator is incrementally relieved of its role as the primary generation source, resulting in measurable reductions in fuel consumption. Notably in Case 5, Gen 1 maintains a fixed output of 300 kW in adherence to the minimum loading constraint, while Gen 2 operates as the reference machine to balance the system. The negative active power readings observed on Gen 2 represent instances where the combined output of Gen 1 and the PV assets exceed system demand and BESS absorption capacity. This results in surplus generation of approximately 48,600 kWh and 39,500 kWh for the months of April and July respectively, which would require curtailment if no additional load or storage outlet is available. This highlights a key operational challenge of enforcing a minimum diesel loading floor in a high VRES penetration scenario, where the inflexibility of the constrained generator can contribute to generation surplus rather than alleviate it. The diesel savings for each case are presented in Table 4, calculated by deducting the total energy generation of each case from that of the base case, then multiplying the difference by the generator's specific fuel consumption of 241 L/kWh at full load sourced from Atlas Copco QAC 1250 (50hz) datasheet, as represented by equation 2:

$$Diesel\ Savings\ (L) = (E_{diesel1} - E_{dieseln}) * (Fuel\ Consumption_{fl}) \quad (2)$$

**Table 4. Diesel generation and savings across all cases**

| Parameter | Case 2 | | Case 3 | | Case 4 | | Case 5 | |
|---|---|---|---|---|---|---|---|---|
| | April | July | April | July | April | July | April | July |
| Total Energy Generated (kWh) | 322,216.27 | 272,000.54 | 318,979.49 | 269,369.26 | 5,913.07 | 19,971.30 | 216,300 | 223,200 |
| Energy savings (kWh) | 109,279.36 | 72,998.08 | 112,516.14 | 75,629.36 | 425,582.56 | 325,027.32 | 215,195.63 | 121,798.62 |
| Diesel Savings (L) | 26,336.33 | 17,592.54 | 27,116.39 | 18,226.68 | 102,565.40 | 78,331.58 | 51,862.15 | 29,353.47 |

### 4.2.7. Battery SOC

The SoC of the BESS units across Cases 3 to 5 provides further insight into the operational behaviour of energy storage under increasing VRES penetration, as presented in Figure 9. In Case 3, both powerhouse BESS units (BESS 7X and 8X) remain near their minimum SOC threshold of 10% throughout the entire simulation period, with only isolated brief spikes. This indicates that the existing distributed PV capacity in Cases 2 and 3 is undersized to generate sufficient excess generation beyond meeting system demand, leaving the powerhouse BESS largely uncharged and unable to actively contribute to diesel displacement beyond occasional opportunistic discharge events.

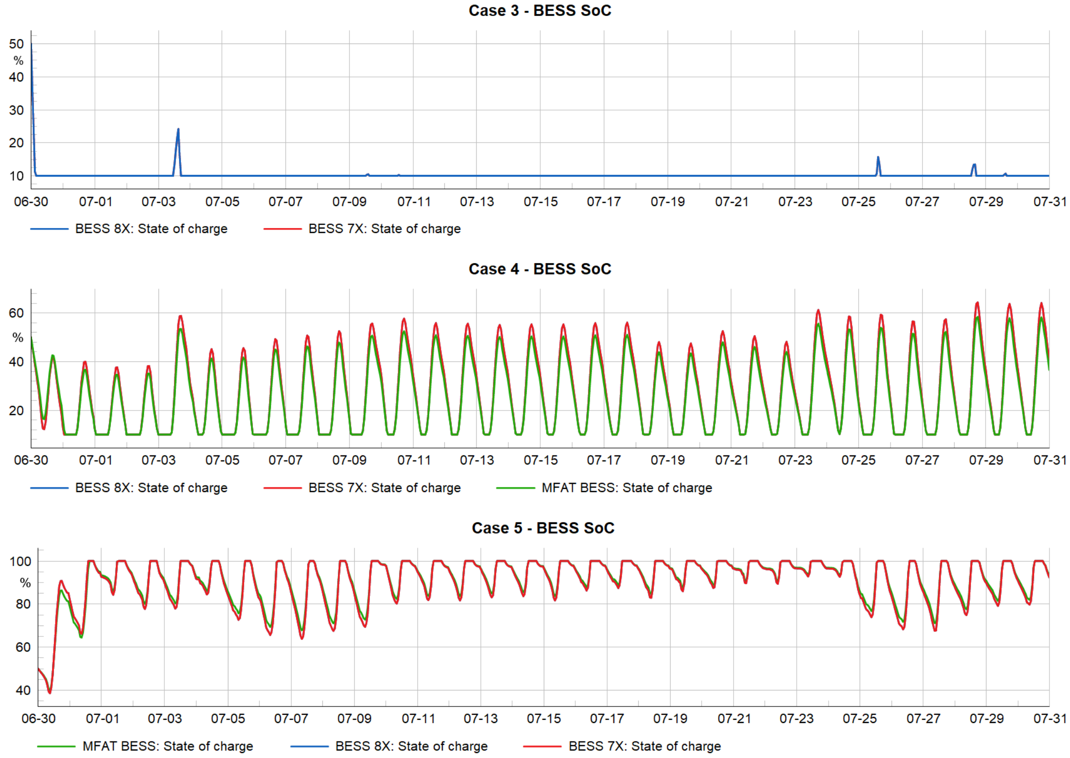


**Figure 9. Battery SoC for Cases 3 to 5**

Case 4 presents a different picture, where the introduction of the MFAT PV capacity provides sufficient excess generation to drive regular and coordinated daily cycling across all three BESS units. The SOC profiles of the powerhouse BESS and the MFAT BESS follow a consistent sinusoidal pattern, charging during solar generation hours and discharging to meet evening and nighttime demand. This confirms that the MFAT PV capacity is the critical enabler of meaningful BESS utilisation across the network.

In Case 5, the imposition of the minimum diesel loading constraint fundamentally alters BESS behaviour. All three units now operate in a significantly elevated SOC range, with their traces closely overlapping, indicating coordinated dispatch. The continuously high SOC is a direct consequence of the constrained DG providing a persistent generation floor that, combined with PV output, charges the BESS faster than system demand can discharge it. As a result, the BESS units frequently approach full capacity without sufficient headroom to absorb further generation, contributing to the surplus generation and curtailment requirements discussed in the previous section. This highlights a tension in a hybrid system operation where establishing minimum loading constraints, while necessary for generator health, can undermine the ability of storage to effectively buffer excess generation.

## 5. Conclusion and recommendations

The simulation results demonstrate that the existing Niue network is adequate to accommodate all five RE transition scenarios, with no line or transformer loading violations recorded across any case. However, the progressive introduction of VRES fundamentally transforms grid behaviour from stable and predictable to increasingly dynamic and event-driven, as evidenced across all monitored parameters including line loading, line losses, transformer loading, and generator loading.

The results further highlight that energy storage is a fundamental enabler of effective VRES integration, particularly in an isolated island grid where there is no interconnection to draw upon during generation shortfalls. However, storage effectiveness is highly sensitive to sizing and integration strategy, as demonstrated by the stark contrast between the near-idle powerhouse BESS units in Cases 2 and 3 and the active coordinated cycling observed in Case 4. BESS effectiveness is contingent on two critical factors: sufficient PV capacity to enable meaningful charge cycling, and appropriate diesel operation practices. While the introduction of the MFAT assets in Case 4 emerges as the critical enabler of coordinated storage utilisation and significant diesel displacement, it also exposes the generator to prolonged low-loading conditions that are detrimental to engine health, accelerating mechanical degradation and increasing maintenance requirements, which has direct implications for the asset management strategies of the country's power infrastructure.

The minimum diesel loading constraint imposed, while necessary to preserve generator health and frequency stability, introduces a fundamental operational tension. The inflexibility of the generation floor, combined with high PV output, saturates the BESS and necessitates renewable curtailment, partially undermining the diesel displacement gains achieved. Furthermore, as diesel generation is progressively displaced across the transition scenarios, the reduction in synchronously connected rotating machinery raises important considerations regarding grid inertia and frequency stability. While modern inverter-based systems are capable of providing virtual inertia through their power electronic controls, this study did not explicitly model frequency response, and sole reliance on virtual inertia in an isolated island grid context carries inherent risks. Collectively, these findings demonstrate that a sustainable RE transition for the Niue grid context requires careful and coordinated optimisation of PV sizing, BESS capacity, and diesel operation, as no single element operates effectively in isolation.

### 5.1. Limitations

Several parameters required assumptions in the absence of detailed literature and field data, including line lengths, transformer loading, and power station and BESS controller schemes. While these assumptions were grounded in engineering judgement and industry practice, access to accurate site-specific data would improve the reliability and precision of the simulation results. Additionally, the absence of field measurements or spot-checks to validate grid behaviour means that the results should be interpreted as indicative trends rather than definitive operational predictions.

Finally, while the simulations provide comprehensive insight into steady-state grid behaviour under varying levels of VRES penetration, frequency stability and the adequacy of virtual inertia provided by inverter-based systems were not explicitly modelled. This is a notable limitation particularly as the progressive displacement of synchronous diesel generation reduces the physical rotating inertia available to the grid, and its implications for frequency response capability under high VRES penetration scenarios warrant dedicated investigation in future work.

### 5.2. Contribution of the research

The findings of this research contribute to the growing body of knowledge on RE transition planning for Pacific SIDS. By systematically evaluating grid performance across five progressive integration scenarios, this study demonstrates that while existing network infrastructure can accommodate increasing VRES penetration, the operation of hybrid systems introduces complex control challenges that must be carefully managed. These insights are directly transferable to other Pacific SIDS with similar isolated grid characteristics and RE transition goals, providing a simulation-based framework that can inform infrastructure planning, asset management strategies, and operational strategies for future transition projects.

### 5.3. Recommendations for further research

Based on the findings of this study, the following recommendations are proposed to guide future research and planning efforts for the Niue RE transition and similar Pacific SIDS contexts:

- A dedicated frequency stability study is recommended to assess the dynamic frequency response of the grid under increasing VRES penetration, particularly as the displacement of synchronous diesel generation reduces available physical rotating inertia and increases reliance on virtual inertia provided by inverter-based systems.
- A comprehensive protection system study is recommended to evaluate the robustness of existing protection schemes against the dynamic and bidirectional power flows introduced by VRES integration, ensuring that relay coordination and fault response remain adequate under all operating conditions.
- Future studies should explore the feasibility of recommissioning previously decommissioned smaller generator units at the Niue power station, which may be better suited to operating efficiently under high VRES penetration scenarios, mitigating the wet stacking risk identified in this study. Where recommissioning is not viable, appropriate technologies that enable existing units to operate reliably at minimal dispatch levels should be evaluated as complementary alternatives, avoiding the need for capital replacement.
- Future work should investigate the integration of flexible loads, such as a desalination plant, as a means of productively utilising excess generation that would otherwise require curtailment. Beyond addressing surplus generation, this approach would simultaneously improve overall system energy utilisation efficiency and deliver compounding social and economic benefits for Niue, particularly in reducing reliance on imported water resources.

- Upon commissioning of the MFAT assets, actual field measurements and spot-checks should be conducted to validate the simulation results presented in this study, with findings used to directly update and refine the grid model with accurate site-specific data, improving its reliability as a planning tool for future studies. Concurrently, a formal operational strategy and energy management framework should be developed to guide real-time dispatch decisions, BESS management, and diesel operation, ensuring the hybrid system maximises renewable utilisation while preserving grid stability and generator health.

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