IRENA
International Renewable Energy Agency

Powering resilient islands
Grid modernisation toolkit for SIDS

ISBN: 978-92-9260-691-6

Citation: IRENA (2025), *Powering resilient islands: Grid modernisation toolkit for SIDS*, International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource, and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

Acknowledgements

The report was authored by Gayathri Nair, with contributions from Rebecca Bisangwa, under the supervision of Simon Benmarraze (IRENA) and the strategic guidance of Roland Roesch (ex-IRENA).

The authors are grateful for the valuable contributions of Rafael Cossent, Ignacio Egido, Pablo Rodilla and Lukas Sigrist (Universidad Pontificia Comillas).

The report benefited from the review and comments of internal experts Ellipse Rath, Paula Nardone, Nadia Mohammed, Danial Saleem (IRENA) and Arieta Gonelevu Rakai, and Omar Marzouk (ex-IRENA). The report also benefited from reviews by external experts, including the late Andrew Lewis (Global Green Growth Institute) and Pramod Kokil (Central Electricity Board, Mauritius); and insights from Mike Lichtenfeld (Solar Pacific Energy Corporation), Sosefo Tofu (Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communications, Tonga), Eden R. Uchel (Palau Energy and Water Administration) and Faustino Yarofaisug (Department of Energy, Federated States of Micronesia).

Editorial co-ordination was provided by Francis Field with the support of Stephanie Clarke. Technical review was provided by Paul Komor. The report was edited by Emily Youers with design by Strategic Agenda.

IRENA is grateful to the Government of Norway for supporting this work.

Disclaimer

Contents

Figures

Tables

Boxes

Acronyms

AI	artificial intelligence
BESS	battery energy storage systems
DER	distributed energy resource
DERMS	distributed energy resource management systems
DMS	distribution management systems
DS3	Delivering a Secure, Sustainable Electricity System
DSM	demand-side management
EMS	energy management systems
ESS	energy storage systems
EV	electric vehicle
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	flexible AC transmission systems
FFR	fast frequency response
FIT	feed-in tariff
FRT	fault ride-through
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
PV	photovoltaic
RoCoF	rate of change of frequency
SCADA	supervisory control and data acquisition
SIDS	small island developing states
SIR	synchronous inertial response
UCED	unit commitment and economic dispatch
UFLS	under-frequency load shedding
VPP	virtual power plant
VRE	variable renewable energy

Definitions

adequacy	The power system's ability to always meet the electric power and energy requirements of the customer. Adequacy describes a system in steady state (*i.e.* a system where voltage and current magnitudes, as well as frequency, do not change significantly with time).
hosting capacity	An evaluation of the maximum amount of wind or solar photovoltaic power that can be incorporated into the system regardless of where they are connected (IEA, 2018).
inertia	The energy stored in large rotating generators that can, for a few seconds, make up for the power lost from a failed generator and resist the drop in frequency (Kundur, 1994; NREL, 2020).
inertial response	The immediate, inherent response (in the form of electrical power) from a device to a disturbance and fall in frequency (AEMO, 2023).
reliability	The ability of a power system to supply adequate electricity on a continuous basis over an extended time period (Kundur *et al.*, 2004).
resilience	System resilience is the capacity of the system to prepare, withstand, adapt and rapidly recover from climate related and other disruptions, while continuing to ensure a sustainable and reliable supply of energy services, with minimal adverse effects on the end-user and minimum loss and damage to critical infrastructure.
SNSP	The system non-synchronous penetration (SNSP), measured as the ratio of real-time megawatt contribution from inverter-based generation (including high-voltage direct current [HVDC] imports) to the demand plus net HVDC exports, measured at an instant in time (EirGrid and SONI, 2018).
security	The degree of risk in surviving disturbances without interrupting customer service. A secure system has a lower degree of risk.
stability	The continuance of intact operation after a disturbance. Stability is an integral component of reliability assessment.
synchronous inertial response	The kinetic energy of a centrally dispatched synchronous unit multiplied by the synchronous inertial response factor. The synchronous inertial response factor is the ratio of the kinetic energy (at nominal frequency) to the lowest sustainable megawatt output the unit can operate at while providing reactive power control (EirGrid, 2022).

SIDS grid modernisation toolkit: **10 actions for transformation**

1 ASSESS AND PRIORITISE
Conduct targeted grid assessments for the inclusion of renewables and evaluate grid modernisation pathways tailored to SIDS.

2 UPDATE GRID CODES
Initiate comprehensive grid code reform, removing barriers to renewables and distributed energy resources.

3 INVEST IN GRID-FORMING DERs
Prioritise investments in distributed energy resources (solar, storage, etc.) with grid-forming capabilities, to improve grid stability and energy independence.

4 INCENTIVISE DEMAND-SIDE SOLUTIONS
Implement demand response programmes tailored to SIDS, promoting 'prosumerism', introducing sector coupling, reducing reliance on imported fuels and offering flexibility

5 SUPPORT GRID SERVICE REVENUE STREAMS
Design policies enabling the participation of distributed energy resources in grid service markets for additional revenue and resilience benefits for SIDS.

6 DEPLOY TARGETED UPGRADES
Target grid upgrades that specifically unlock the capabilities of distributed energy resources and enable them to support the grid, considering SIDS specificities and economic constraints.

7 PLAN PROACTIVELY
Shift from reactive to proactive grid planning, using modelling tools that simulate future scenarios with high distributed energy resource integration and sector coupling.

8 ENSURE UPSKILLING AND KNOWLEDGE TRANSFER
Establish programmes focusing on building and enhancing local technical capacity in grid operation and modernisation, emphasising demand-side management, distributed energy resource operations, and maintenance.

9 ENGAGE COMMERCIAL CONSUMERS
Collaborate closely with large energy consumers (hotels, industries) to create tailored distributed energy resource solutions to enhance grid stability, improve resilience and reduce energy costs.

10 SHOWCASE SIDS INNOVATION
Proactively promote case studies and success stories within the SIDS community and globally to share best practices to attract funding, positioning SIDS as leaders at the forefront of the energy transition.

Executive summary

Despite their very minor contribution to global greenhouse gas emissions, small island developing States (SIDS) are exceedingly susceptible to climate change. Alternatives to fossil fuels, and their associated price volatility, are renewable generation resources, which provide a sustainable and cost-effective solution to climate change. These renewable resources provide the additional advantage of improving the resilience of energy systems, enabling them to withstand disruptions from extreme weather events.

SIDS have demonstrated their commitment to the energy transition in their nationally determined contributions. The growth in renewable deployment in SIDS rose around 150% from 2014 to 2023. SIDS have reached a renewable deployment of 8.7 gigawatts (GW), with solar photovoltaic additions at 4.21 GW, plus modest shares of hydropower, wind and bioenergy generation (IRENA, 2025). Through the use of innovative solutions and technological evolutions, SIDS have maintained their momentum on the energy transition. Though the benefits of renewable energy are widely known, SIDS continue to face the challenge of reaping these benefits owing to a variety of obstacles, including those linked to the implementation and operation of renewable energy projects, which require adequate financial resources, institutional capacity, technology transfer and human skills.

IRENA has been working to support SIDS in their transition to renewable energy, which is a key step towards them achieving their sustainable development goals. IRENA's support has included the provision of platforms for the exchange of knowledge and peer-to-peer learning on topics like project financing and enhancing the bankability of projects. Capacity building and technical assistance are also part of the IRENA spectrum of support, including investigating the capacity of the power sector to include higher shares of renewables. This report brings together the methodology and recommendations that have emerged from these technical studies, which have highlighted the hosting capacity of the power systems to renewables, especially variable renewable energy (VRE).

The IRENA studies can be categorised as either technical or techno-economic. The focus of these studies has been to assess the power network and its limitations in relation to the integration of renewable generation, particularly the variability and uncertainty inherent in the nature of solar and wind power. The system operator can also be challenged by the inverter-based nature of these resources, which necessitates a greater degree of flexibility. The studies recommend solutions that can improve system performance and allow the integration of higher shares of renewables. Security assessment of the grids provides information on the impact of VRE on system reliability as well as the static and dynamic security of the power system.

The primary concern for island grids is grid stability - particularly frequency stability when there is limited inertia as the proportion of solar and wind generation increases - and phasing out synchronous generation units, according to insights from IRENA studies. The ageing infrastructure in the majority of SIDS is another factor, as the current system frequently lacks the flexibility and grid support capabilities required for the seamless integration of VRE. The deployment of distributed energy resources and innovative technologies is also impeded by outdated regulatory frameworks, such as tariff structures, grid codes and a lack of enabling policies. Two critical challenges are the absence of a transparent and supportive regulatory environment and the prevalence of permitting obstacles. It is also imperative to improve the technical capabilities of staff to ensure the effective implementation and absorption of new technologies.

IRENA studies recommend cost-effective and system-specific solutions at both infrastructure and operational levels, which can enhance the system's ability to include more VRE. Specific solutions that can improve system flexibility include storage and smart operational measures. Upgrading the system to improve voltage and overload situations, using innovative technologies (*e.g.* smart meters, SCADA (supervisory control and data acquisition) and grid-forming inverters) to accommodate the different actors in the system, is recommended. Technologies that can support better observability and controllability of systems and enable sector coupling, such as demand-side management measures, have also been highlighted. Better balancing and reliability can be ensured if consumers can respond to grid disturbances by adjusting consumption patterns. The studies highlighted the need to modify grid codes, especially on the prerequisites for connecting renewable generators, so that they function in a grid-supporting manner.

IRENA conducted a survey and interviews of stakeholders from 26 SIDS and identified the key obstacles that still exist in the uptake of renewables, related to the financing, policy making and implementation of renewable energy projects. The information gathered underlined the need for an enabling framework, including reformulating tariffs, improving connection times and processes, developing skills, and reforming subsidies. It highlighted the need for more detailed techno-economic analysis and innovative financing solutions. The smaller market size, unfamiliar regulatory regimes, and perceived risks are still seen to be impeding the financial resources required for the accelerated uptake of renewables and grid modernisation by SIDS.

1 Introduction: The SIDS energy imperative

1.1 The challenges and opportunities for SIDS

Renewable resources have the capacity to improve energy security and reduce emissions, in addition to using local resources and reducing dependence on expensive fossil fuels. Small island developing States (SIDS) can and have realised some of these benefits in decarbonising their energy systems. To fully realise these opportunities, the power systems need to be modernised to accommodate diverse devices into the system; creative financing models and long-term holistic planning are also needed to address the technical constraints raised by variable renewable energy (VRE).

The vulnerability of SIDS to climate change is escalated by their geographical location, instability in the fossil fuel markets, and severe weather events. SIDS are impacted by the price volatility of fossil fuel, further impacting their socio-economic progress. With their smaller market size, they do not have the advantage of economies of scale and therefore have increased reliance on foreign markets. Greater geographical distance from larger markets means higher costs for energy and infrastructure. SIDS face extensive destruction from extreme events, which have increased in frequency and intensity. There is great need, therefore, for SIDS to develop robust systems that can be resilient to both extreme events and market-related fluctuations.

One major action that needs to be taken to meet climate action goals is to include substantial shares of VRE in the power grid while continuing to maintain the grid's reliable and efficient operation. Grid modernisation and expansion are essential elements that can enable this. Hence, the challenge for SIDS is twofold: enhancing their renewable energy capacity and bolstering their resilience. It is crucial to comprehend these two challenges in order to successfully address them and guide the sustainable energy transition of SIDS.

The integration of VRE into the power grid facilitates decreased dependence on expensive and environmentally detrimental fuels. Although solar and wind energy offer cost-effective and localised alternatives to fossil fuels, their incorporation into power grids poses technical constraints. They are inverter-based systems and possess inherent variability. These systems do not contribute to grid supporting functionalities inherently, and they require more flexible operation of the system. The locational constraints of these resources result in a greater degree of dispersion, which adds to the constraints imposed by the characteristically small size and fragmented nature of island power systems. The intermittency of variable renewable generation is frequently difficult to manage due to the limited flexibility of existing infrastructure, and the dynamics of the power system are altered by the incorporation of high levels of VRE generation.

VRE integration is not limited to the transmission system level; it also occurs at the distribution system level. It can be either grid connected or off-grid. In systems that were historically designed for unidirectional power flow, grid-connected distributed generation introduces reverse power flows. This requires improved management of voltage and reactive power by the distribution operator, as it affects the system's voltage profile. Traditional synchronous generation, which is responsible for grid-supporting functions such as inertia and reactive power support, is replaced when VRE are incorporated at the system level. To reduce the consumption of fossil fuels, it is imperative to modernise the infrastructure and ensure that renewable resources operate at their optimal levels. This modernisation should be the outcome of a comprehensive planning exercise, aligned with the specified renewable energy targets.

Power system planning encompasses many levels of assessment, including renewable resource planning, transmission planning, generation planning and grid upgrade planning. An effective planning process will ascertain the primary requirements for the future power system and will sometimes include regional planning, encompassing several administrative regions. A grid integration study is a component of this process whose primary goal is to evaluate the performance of the power system and ensure its cost-effective operation with high levels of variable renewables. These studies provide recommendations on how to address the constraints of incorporating wind or solar photovoltaic (PV) sources by implementing new enabling technologies or operational strategies or by redefining network regulations.

Strengthening resilience entails assessing the current degree of resilience and identifying crucial actions that will enhance disaster resilience. The evaluation of resilience should ideally lead to the development of a comprehensive framework for resilience, and it is advisable to conduct these studies during the first phases of the planning process as they offer valuable input for the analysis of security.

IRENA facilitates technical grid assessment studies as technical assistance to SIDS in identifying the challenges associated with integrating high shares of VRE into their power grids. These studies highlight the technical constraints associated with operating the grid with larger proportions of VRE and propose measures to overcome those constraints. These studies highlight that to attain a decarbonised power system, SIDS must adopt a comprehensive and inclusive planning process that takes into account investments in enabling technologies, and other crucial factors that enhance system flexibility and maximise the potential for renewable integration. Furthermore, the effective integration of VRE into the system could be facilitated by enhancing defence mechanisms, increasing the resolution of dispatch and improving the control of generation units, establishing connections with neighbouring islands, and implementing curtailment when necessary. Modifying grid codes to accommodate new technologies and providing transparent rules for the interconnection of new generation sources in a grid-friendly manner can help the system operate securely and safely. Weather and VRE forecasting, in conjunction with distribution automation and storage systems, can contribute to better reliability and flexibility of the system.

Smart grids, sophisticated monitoring and metering infrastructure, and demand response programmes are crucial instruments to provide adaptability, enabling consumers to actively participate in the energy transition. Targeted policy interventions, knowledge exchange, affordable financing and international collaboration are crucial to facilitate the transition. By adopting a comprehensive grid modernisation plan customised to the unique requirements of SIDS, the foundation for a more secure, sustainable and equitable energy future can be established for these states.

1.2 Objective and structure of the report

This report discusses the different steps and solutions that system operators need to undertake to build a reliable, resilient and low-carbon grid.

Chapter 2 discusses the typical approach that IRENA has been taking since its inception in supporting SIDS in their transition to renewable energy. It highlights the different levels of engagement and details the scope of the studies.

Chapter 3 provides a discussion of the grid assessments that IRENA has conducted for SIDS. The main challenges identified and the recommendations made from each of the studies are detailed. How the different studies were conducted, and their interlinkages, are also discussed.

Chapter 4 provides a detailed discussion of the main obstacles to and main drivers for the integration of renewable energy sources as identified by IRENA.

Chapter 5 discusses a toolkit for developing resilient island grids, including infrastructure upgrades, operational measures, improved flexibility through ancillary services, and cross sector coupling as recommended by the IRENA grid assessment studies.

Chapter 6 provides a more detailed discussion of solutions, including market regulations, that can improve flexibility and grid stability beyond theoretical VRE thresholds, offering tailored recommendations on specific technologies, grid codes, control schemes and operational practices. This discussion includes examples of innovative solutions and technology enablers that have emerged recently and have found applications in island power systems.

Chapter 7, derived and validated by the survey and interview of SIDS stakeholders, discusses the enabling frameworks and incentives that could promote the accelerated uptake of renewables in SIDS, including innovative financing, tariff setting and incentives for diverse configurations of renewable technologies.

2 IRENA studies for island grid decarbonisation and modernisation: Approach and scope

IRENA has been a steadfast partner for SIDS, providing technical expertise and resources to support their energy transformation journeys. IRENA's extensive portfolio of technical grid integration studies serves as a valuable knowledge base for SIDS. To date, IRENA has conducted grid integration studies on several islands, as shown in Table 1.

Table 1 List of IRENA grid assessment studies for SIDS

Island	SIDS	Region
Aitutaki	Cook Islands	Pacific
Antigua	Antigua and Barbuda	Caribbean
Dominican Republic	Dominican Republic	Caribbean
Espiritu Santo	Vanuatu	Pacific
Palau	Palau	Pacific
Upolu	Samoa	Pacific
Viti Levu	Fiji	Pacific

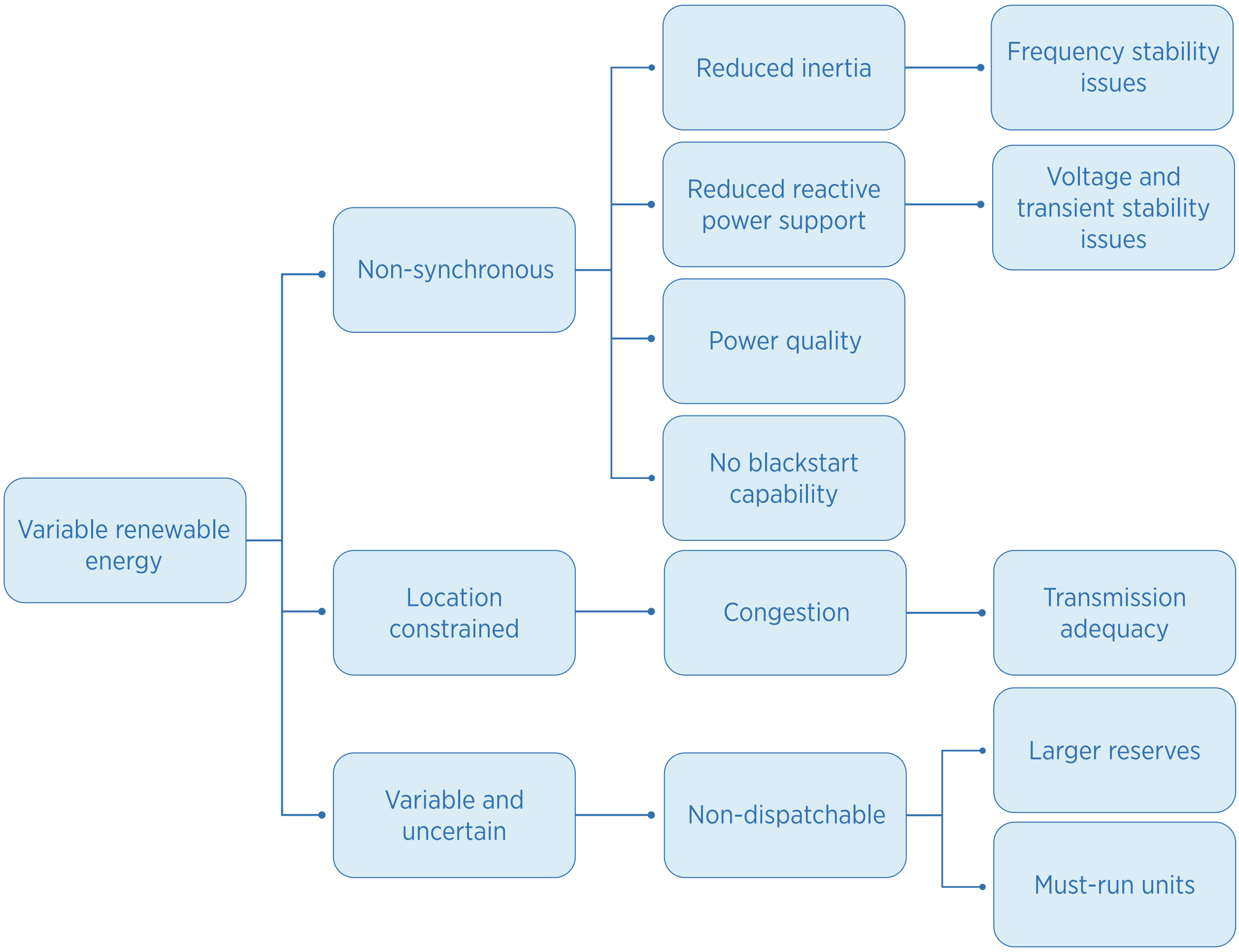
IRENA's grid integration studies employ advanced modelling and simulation techniques to investigate the complexities of island power systems. These analyses offer a thorough assessment of the system's capacity to accommodate high levels of VRE. Figure 1 illustrates a few of the technical constraints that the system operator is subjected to as a result of the incorporation of high proportions of VRE.

A comprehensive assessment of grid preparedness for incorporating renewable energy sources should include a series of studies to identify the measures necessary to enhance the system's capacity to accommodate renewable energy sources. Three major classifications of such studies are the system or capacity expansion study, the production cost or unit commitment and economic dispatch (UCED) study, and the security assessment or grid assessment study. Their execution spans various time frames and yields diverse solutions. The selection of which study or combination of studies to execute is contingent on the policies and targets set by the country to address its specific priorities. For instance, when planners are assessing the optimal energy supply mix to achieve long-term policy objectives, a study on expanding the system may be highly beneficial, particularly if it is complemented by UCED analysis to test the operational impacts of various expansion plans. In contrast, if power system planners and operators aim to prioritise short- and medium-term measures to enhance the flexibility of the power system, production cost analysis may offer the most suitable framework.

A reliable power system is both secure and stable. The reliability of a power system is evaluated by examining its adequacy and security. When power system requirements – such as load, voltages and frequency – are met, a system is considered adequate. VRE generation sources like solar and wind are non-synchronous in nature and is non-dispatchable. It replaces the inherent grid-supporting functionalities of synchronous generators. For example, the absence of rotational machinery in the grid reduces its capacity to provide inertia, which could result in frequency stability issues. Assessments of the system under consideration are needed to develop a detailed understanding of system-specific issues and to determine the most suitable solution.

The power system security is linked to the dynamic transition between system states, which in turn determines its steady-state conditions. A secure state is not necessarily an adequate state, and the reverse is also true. The implementation of operational, control and protective measures is essential for the security and adequacy of system state. Sluggish use of practical reserves is highly likely to lead to a total blackout, brownout or load shedding, even if there are enough reserves. Island systems that deploy a lesser number of generating units, in comparison to larger interconnected systems, are typically restricted in terms of the time available for reserve deployment.

Figure 1 Characteristics of variable renewable energy and associated challenges



2.1 Adequacy assessment

An adequacy assessment evaluates the system's capability to meet demand under various conditions in long-term planning scenarios. System adequacy is a measure of the power system's ability to supply load within certain standards and is analysed through generation and transmission adequacy. Generation adequacy refers to the capacity of a system to effectively balance demand and electricity production; transmission adequacy refers to the system's ability to efficiently handle the flow resulting from both demand and production. Box 1 highlights Barbados as an example of the adequacy issues islands can face.

Adequacy indices can be quantified using two primary methods: analytical techniques and simulation techniques.

- Analytical techniques represent the system using a mathematical model; they evaluate expectation indices (*e.g.* loss of load expectation or expected energy not supplied) from this model by using direct numerical solutions.
- Simulation techniques calculate indices and, more specifically, their probability distributions by replicating the real process and random behaviour of the system through simulation of a sequence of actual experiments. The resulting stochastic simulation can be either random or sequential, contingent on the choice of fundamental simulation intervals.

Consequences of grid inadequacy

Box 1 Challenges in Barbados due to grid inadequacy

Barbados exhibits challenges linked to grid insufficiency. The Barbados Light and Power Company has encountered grid stability challenges. The Company is unable to integrate more than 100 MW of renewable capacity, yet has received 333 MW of renewable energy license applications. The Company communicated that further connections would be possible only if developers either agreed to curtailment, or provided energy storage solutions to accompany their projects. Further connections will now be subject to the completion of grid modernisation efforts. This has caused uncertainty amongst project developers, some of which already have projects under construction and who face considerable uncertaintly with regard to connectivity and associated timelines. Therefore, modernising the grid to enhance efficiency and flexibility is a crucial measure to incorporate renewable energy sources and consequently decrease reliance on fossil fuel-based power generation.

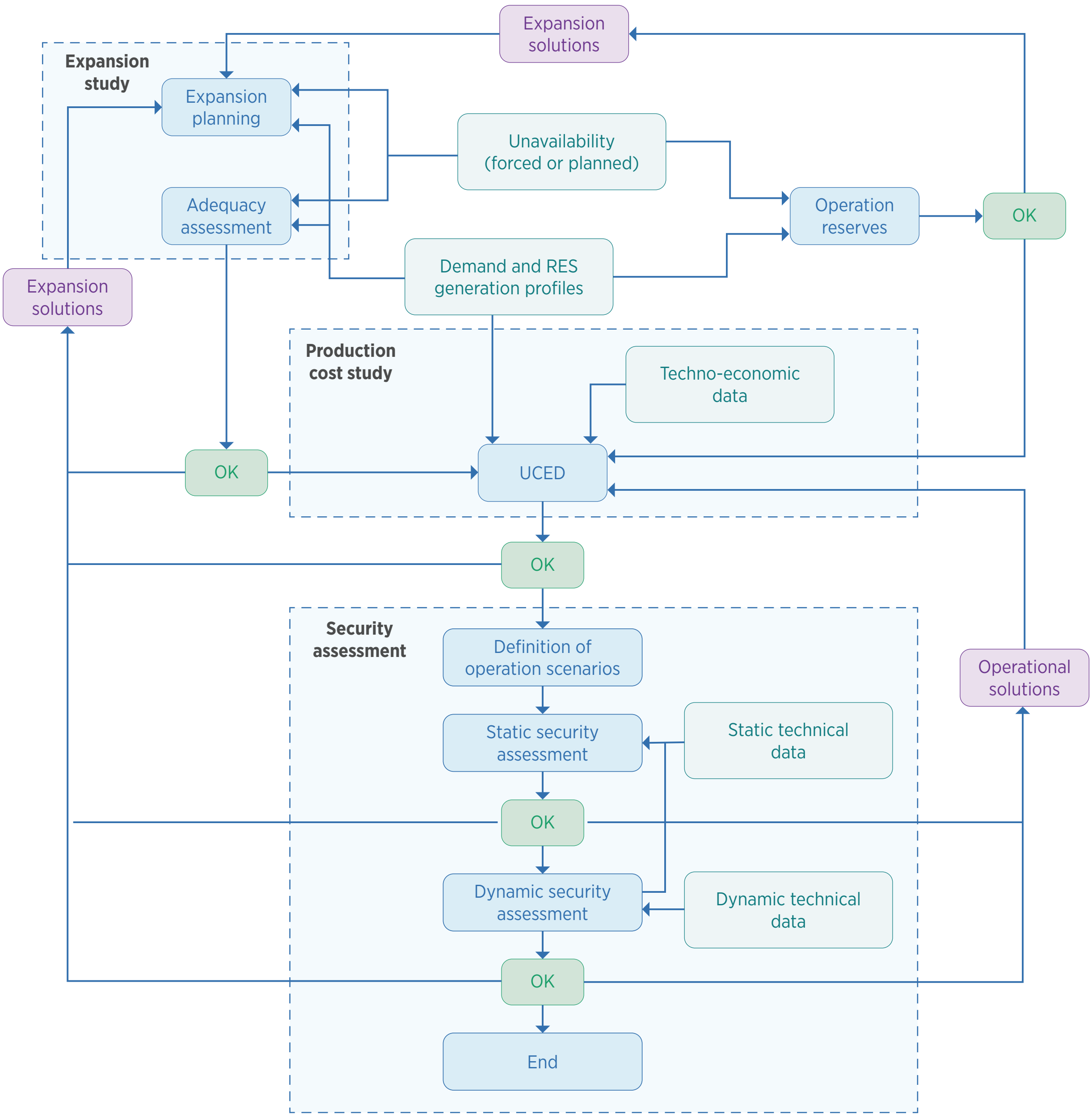
Source: (BREA, 2025).

The state of the system at a specific instant can be categorised in the following ways (Kundur, 1994):

- normal state (or adequate state), where the system variables are within normal range and no overloading happens
- alert state, where while system variables are in an adequate state, the system security level is below normal, with high possibility of contingency.
- emergency state (inadequate), where the system variables exceed emergency ratings

One way of ensuring system reliability is the allocation of adequate operational reserves. The operational reserves are determined by simulating the detailed UCED under the assumption of sufficient expansion plans, prior to the calculation of the production costs. They consider the intra-hour variability of renewable energy sources and demand and, optionally, the greatest generation-load imbalance. A UCED is a typical optimisation problem that seeks to reduce variable operation costs. This establishes the commitment status and power generation set point on an hourly basis over a specified time period, as well as simulations of production costs. The UCED's time frame may fluctuate from one week to the following day, depending on the operational protocols. The techno-economic parameters of the generating units, including fuel cost curve parameters, start-up costs, operations and maintenance costs, maximum and minimum capacity and ramp rates, minimum up and down periods, and emission penalties, are all considered in this problem. Furthermore, it encompasses constraints associated with system operation and generation units, including reserve requirements and must-run units.

Figure 2 Sequence of studies and relationships for grid assessment



Notes: RES = renewable energy sources; UCED = unit commitment and economic dispatch.

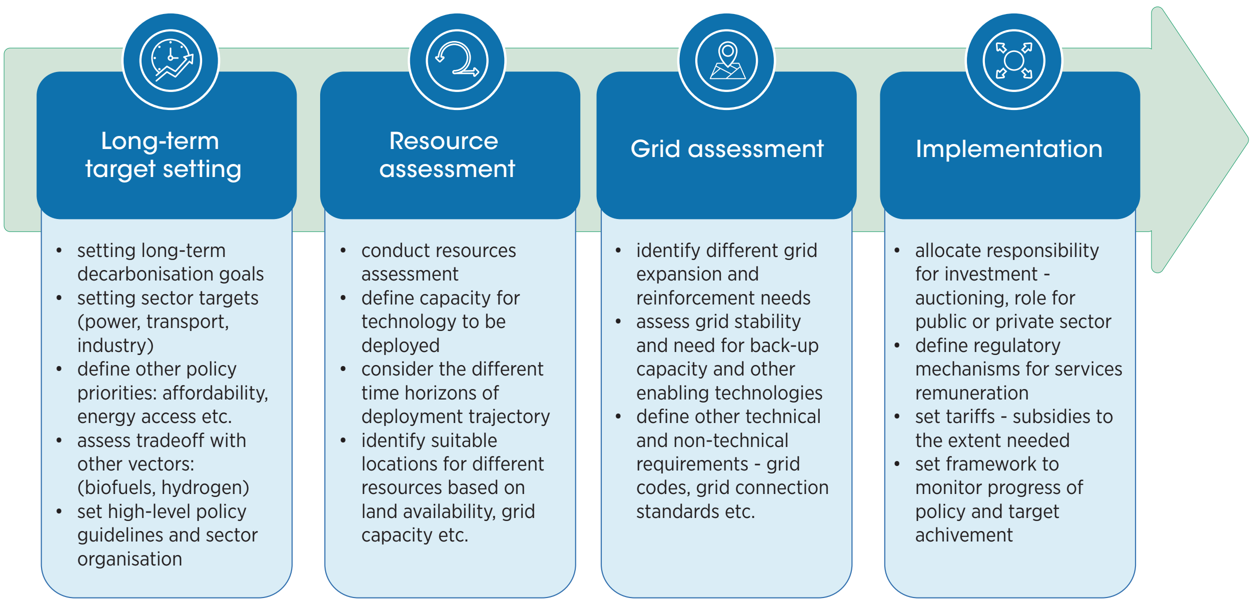
This toolbox shown in Figure 2 outlines the chronological order of studies that need to be conducted to evaluate the hosting capacity of the system for renewable energy sources. System expansion studies establish the scenarios for production cost simulations, which subsequently establish the parameters for security evaluation investigations: a clear, predefined sequence. Security assessment is based on the functional zones, namely the generation-transmission system (bulk system) and the distribution system.

2.1 Grid assessment

Operating scenarios may be selected from the UCED simulation and subsequently assessed for system security, which is the focus of grid assessment studies. Technical and techno-economic examinations are two categories into which grid assessment studies can be classified. Technical studies commence with the generation dispatch scenarios that are specified by the UCED. Techno-economic studies typically involve establishing the commitment status and power generation set point using the UCED.

For grid assessment studies to be useful, they need to be properly co-ordinated with policy targets and aligned with short- to long-term operational decisions, which are conditioned by the regulatory framework in place. This means the scenarios and assumptions considered in the assessment must be appropriately aligned with the overall policy targets as well as with the investment and operational decisions made by all relevant stakeholders at the implementation stage. This requires a streamlined and co-ordinated process, as illustrated in Figure 3. For instance, an assessment based on scenarios inconsistent with the national policy targets would not be practical. Likewise, an assessment perfectly aligned with the national policy views would be useless if the investment decisions made by utilities or independent power producers are completely independent of those policy views. This is why adequate stakeholder engagement, and an enabling regulatory framework are essential.

Figure 3 Requirements to co-ordinate policy target-setting with grid assessment studies and resource investment decisions



The objective of security assessment is to address the system operator's concerns regarding the potential reliability impacts that renewable energy sources, particularly VRE sources, may have on the power system's operation. Grid assessment studies evaluate the capacity of a power system to accommodate significant modifications in demand and generation that may arise during the planning process, such as expansion, renewal or asset substitution. They also analyse the static and dynamic security of the power system, with an emphasis on future demand and generation scenarios. As mentioned above, the security assessment is informed by the estimation of production and expansion costs. Simulation software that accurately replicates the power system is employed to conduct the analysis.

A secure system is characterised by its ability to transition between system states using the precondition that:

- The system settles into a new operating state and no physical constraints are violated.
- The system survives the transition to these new conditions.

According to these two requirements, security assessment can be divided into static and dynamic security assessment:

- The static security assessment is a steady-state analysis of the system after disturbance to ensure that no constraints are violated.
- The dynamic security assessment is the evaluation of system stability under various classes of system stability. Dynamic security analyses typically focus on the security of transmission systems, as faults in the transmission system are generally more critical to system security than faults in the distribution system.

The technical network studies involve static and dynamic security analysis conducted over time frames of a few seconds to a few minutes.

Static analysis

Static analysis encompasses a load flow study conducted under both normal and abnormal operating conditions, also referred to as contingency analysis, together with short circuit studies.

- Load flow studies under normal conditions determine the voltage magnitudes and angles, real and reactive power flows, and system losses.
- Short circuit studies determine the short circuit power for given buses, a quantity commonly used to limit VRE penetration, based on the impact it has on protection devices.

Evaluation: Typically, the power system is built and operated to endure a certain set of potential failures known as "normal" or "credible" contingencies (*e.g.* N-1 or N-2 criteria), which are chosen based on their high probability of incidence. The abnormal operation is a collection of plausible scenarios, typically involving the loss of at least one transmission or generation element (N-1 criterion).

Criteria: Voltages and branch flows of transformers and lines must be within predetermined limits, which differs for normal and abnormal operation and as stipulated in grid codes. Typically, high-demand scenarios are more critical for branch overloads and low-voltage conditions, whereas low-demand scenarios may exhibit high-voltage conditions. A representative set of hourly demand and renewable energy generation scenarios should be considered for technical studies.

Dynamic analysis

Dynamics analysis encompasses the use of dynamic simulation studies to assess the stability of the power system. System stability can be categorised into three types: rotor angle stability, frequency stability and voltage stability, based on following characteristics:

- the physical nature of the instability
- the size of the disturbance
- the devices, the processes and the time span

The primary issues of an island power system revolve around frequency and transient stability, as they directly impact the operation of its generators. In general, the assessment of frequency stability involves the simulation of a significant power imbalance. Conversely, transient stability is evaluated by simulating short circuits on representative buses and lines. Box 2 highlights the stability classification as considered in security assessment studies (Hatziargyriou *et al*., 2021; Kundur, 1994).

Box 2 Stability classification and assessment

- Rotor angle and voltage stability: Can be categorised into small and large disturbance stability based on the magnitude of the disturbance and the linearisability of the governing equations (large disturbance rotor angle stability is also known as "transient stability").
- Frequency and voltage stability: Can be categorised into short- and long-term stability based on predominant dynamics. Short-term frequency stability is mostly influenced by inertia and primary frequency control; long-term frequency stability is further influenced by turbine dynamics, automatic generation control and available reserves.
- Resonance stability and converter-driven stability: The integration of renewables, especially inverter-connected generation, has led to a new stability classification of resonance stability and converter-driven stability in the new environmental paradigm.

Simulation models

Technical investigations are conducted using static and dynamic simulation models. The dynamic models incorporate time-dependent responses formulated through ordinary differential equations.

- Static models refer to the network model and its parameters (line and transformer parameters, fixed or variable shunt device parameters, etc.).
- Dynamic models refer to models of the generating units, fixed or variable shunt devices, flexible alternating current (AC) transmission systems (FACTs), and so on.

These assessments are typically conducted using simulation software packages such as DigSILENT and PSS/E, as chosen by the system operator.

2.1.1 Grid assessment: objectives

Grid assessment studies are integral to the grid integration process and can be conducted with varying degrees of specificity and in pursuit of specific objectives. These assessments consider existing resources and suitable sites for project development, expansion strategies, and operational scenarios.

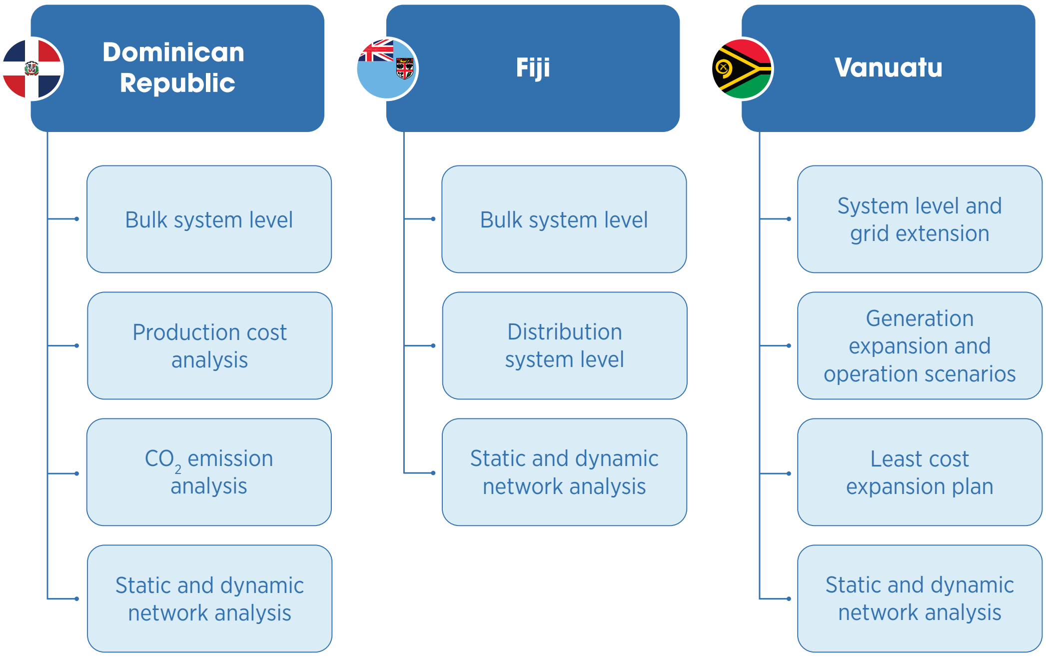
The primary objective of grid assessment studies, in case of SIDS, is to assess the system's ability to host renewable energy sources, particularly VRE sources, and to suggest solutions that facilitate decarbonisation of the power system. Key steps include:

- **Evaluating grid stability:** These studies evaluate system dynamics under varying generation and demand profiles, with particular attention given to voltage and frequency stability, transient behaviour, and the evolving need for renewable sources to provide grid support.
- **Load flow studies:** In general, load flow studies are carried out for normal and abnormal operation conditions and by considering the N-1 criterion for branches and generation.
- **Security assessment:** A static security assessment involves the steady-state assessment of the system before and after a disturbance.

Through detailed evaluations of existing grid infrastructure (transmission, distribution and generation), the system's ability to host VRE can be determined, identifying potential bottlenecks, expansion requirements and the associated costs of necessary upgrades. A further objective is to identify enabling solutions. The studies highlight the technology enablers that can boost the hosting capacity of the island power system. These enablers can be general infrastructure investments and operational measures.

Figure 4 shows examples of different types of study conducted based on these countries' request and the specificities of their power systems.

Figure 4 Example scopes of studies conducted for three SIDS



Note: CO_2 = carbon dioxide.

2.1.2 Grid assessment: scope

To enhance the security of the power system, it is imperative that any island that aspires to increase the proportion of renewable energy sources in its system, particularly VRE sources, executes a comprehensive static and dynamic security assessment, followed by a protection co-ordination study. Additionally, its scope or limits should be well defined. The scope of the study determines whether it specifically assesses the bulk power system and/or the distribution system, considering that the renewable addition could happen at utility scale and at the rooftops. In certain systems, the distribution system can be further divided into medium-voltage and low-voltage systems, as well as aggregate system studies that may also include sub-transmission systems. The classification of transmission, sub-transmission and distribution systems is system specific. The scope's precise limit is contingent on the power system under analysis and the specific location where renewable energy, particularly VRE generation, is growing in numbers. The voltage levels of smaller islands are placed in the generic distribution system category, specifically 20 kilovolt (kV) networks or lower, while larger island systems comprise high-voltage transmission grids, such as 220 kV and 66 kV.

Most distribution system evaluations, particularly those that involve medium- and low-voltage systems, involve static security analysis. A Thévenin equivalent of the bulk system at the site of connection to the distribution system is used for simulation. Static security analyses evaluate both sequential and instantaneous load flow characteristics. Sequential load flow evaluation can help identify issues with the steady-state operation of on-load tap changers, such as tap cycling.

Both static and dynamic security analysis are included in the examination of bulk systems. Typically, these studies employ a comprehensive representation of sub-transmission systems, while medium- and low-voltage systems are represented by static and dynamic equivalents. Conducting short circuit studies necessitates an accurate representation of the short circuit power at the point of interconnection. The increasing prevalence of VRE necessitates that the dynamic equivalents accurately represent the dynamics of VRE generation units for the evaluation of stability.

Table 2 Priority of characteristics for sub-scenario selection

Criteria	Valley demand	Peak demand	Mean demand
Demand	Low	High	Low
Number of units connected in the dispatch	Low	Low	Low
Power output of the largest unit connected	High	High	High
VRE generation	High	High	High
Spinning reserve	Low	Low	Low
Inertia	Low	Low	Low

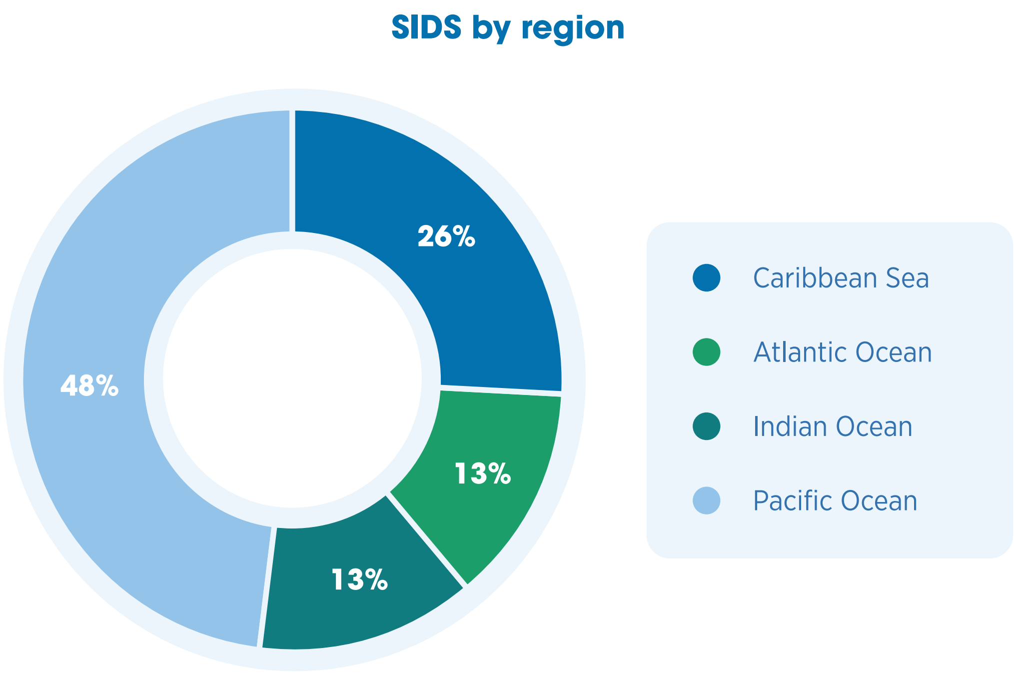
Another detail within the scope is the selection of sub-scenarios or critical snapshots of the study, including the correlation between a low-VRE and high-demand scenario, a high-VRE and low-demand scenario, and/or a mean demand scenario. This evaluation of sub-scenarios will provide key insights about the most stressed system behaviour. The selection of a low-demand (valley) and high-demand (peak) demand scenario for evaluation can be characterised as shown in Table 2. The table shows how the factors of inertia, spinning reserve, VRE generation, power output of the largest generator, number of units in dispatch, and demand can be prioritised for each sub-scenario selection. For low-demand (valley) scenarios, the impact of the power output of the largest generator and the VRE generation profile have the highest impact, as during low demand the prevalence is to operate fewer units with higher ratings as a cost-effective option and the loss of this generating unit could lead to cascading outages.

Enhancing grid evaluation frameworks to give priority to these specific factors related to SIDS enables policy makers and energy planners to make well-informed choices regarding investments and regulatory frameworks. This targeted approach will expedite the progress of SIDS toward modern, resilient and sustainable energy systems. A comprehensive analysis of previous grid assessment studies enables the identification of a set of tools for conducting such studies.

2.2 IRENA survey of stakeholders

IRENA conducted a survey of 52 stakeholders in the SIDS energy sector to obtain insights into the challenges that these islands still face in accelerating the adoption of renewable energy sources and upgrading their power grids. Figure 5 shows the geographical spread of the SIDS from which stakeholders responded to the survey.

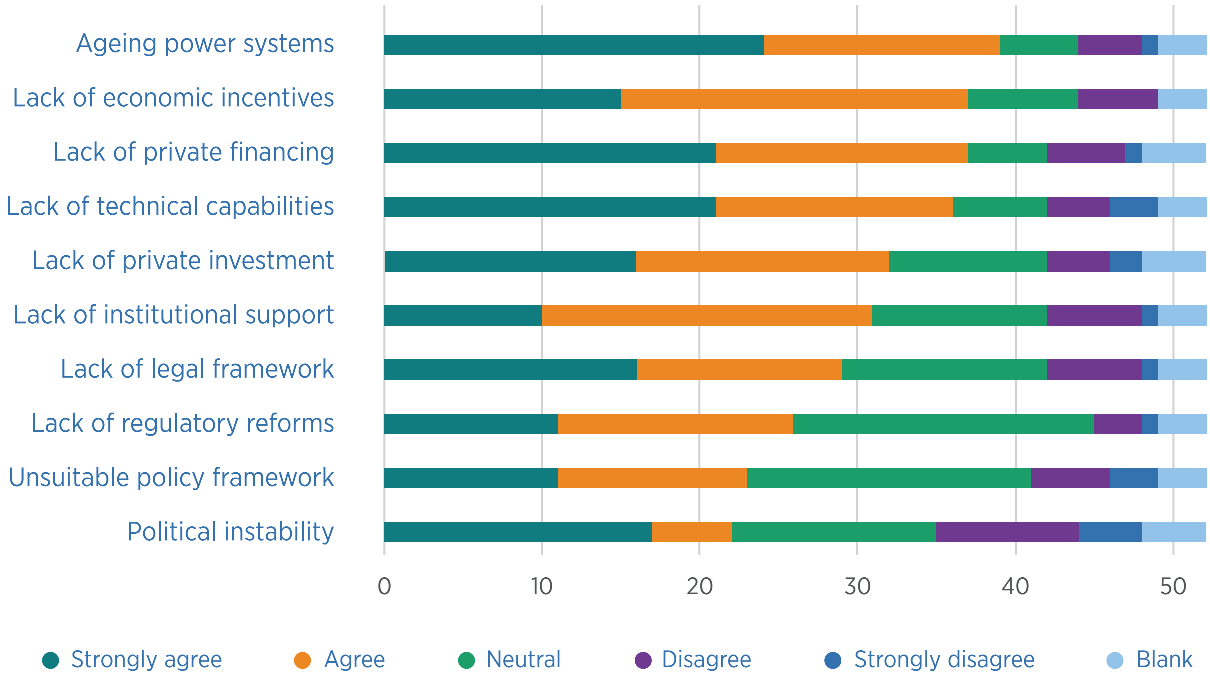
Figure 5 Number of SIDS, by region, from which stakeholders responded to survey



The survey collected feedback on the present policy and regulatory framework for the integration of renewable energy resources into the power grid. This information was essential for the identification and understanding of current practices, which in turn facilitated the development of a set of policy insights that would enable the accelerated uptake of renewable power generation in the future. The survey evaluated policy objectives; techno-economic evaluations that substantiate energy policy objectives; obstacles and impediments; and economic and valuation indicators.

One of the key outcomes from the survey was the identification by the stakeholders of existing barriers to increasing the share of renewable energy generation, as shown in Figure 6. Ageing power systems, lack of economic incentives, lack of private financing and lack of technical capabilities ranked high on the list of these barriers. More discussion on this is provided in chapter 7.

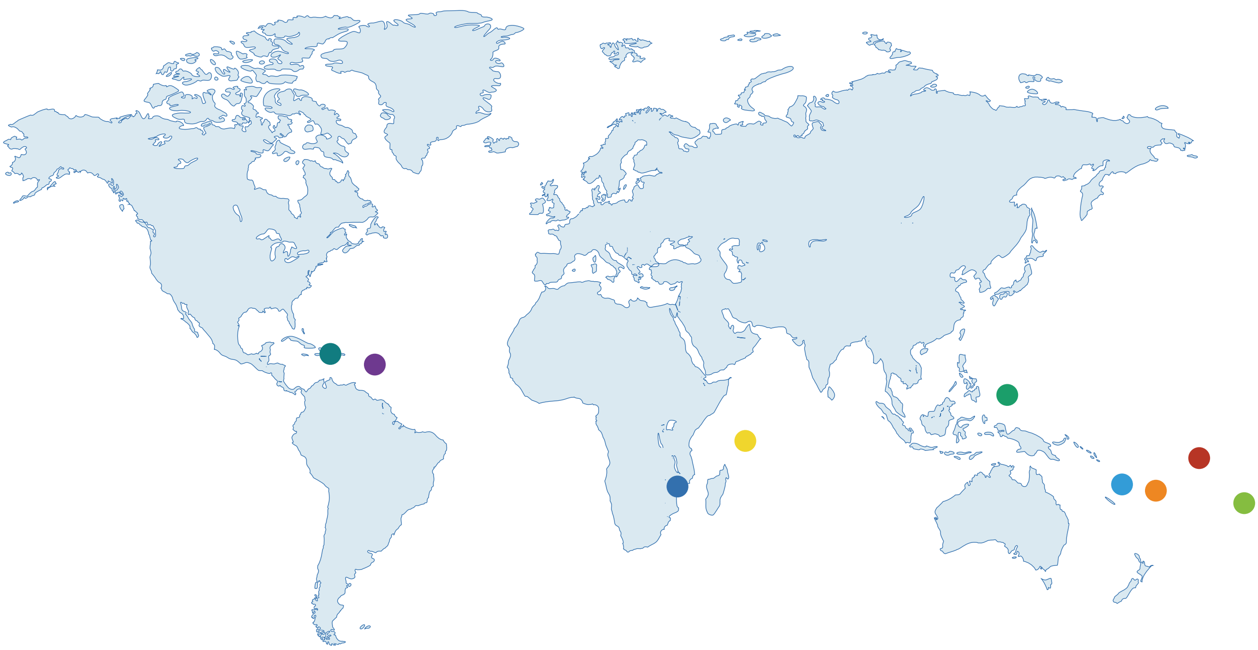
Figure 6 Responses on barriers to increasing the share of renewable energy generation in SIDS



3 Insights from IRENA grid studies

IRENA's grid integration studies on various islands highlight both the opportunities for and the technical complexities of high VRE integration in SIDS environments. Figure 7 highlights the list of grid assessment studies conducted by IRENA for SIDS. IRENA studies move beyond theoretical VRE thresholds, offering SIDS tailored recommendations on specific technologies, grid codes, control schemes and operational practices that optimise the integration of variable renewables within their unique grid contexts.

Figure 7 Locations of grid assessment studies completed by IRENA



- Dominican Republic (2019)
- Antigua and Barbuda (2015)
- Mozambique (2022)
- Seychelles (2022)
- Palau (2013)
- Vanuatu (2018)
- Fiji (2019)
- Samoa (2014, 2016)
- Cook Islands (2015)

Disclaimer: This map is provided for illustration purposes only. Boundaries and manes shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitations of frontiers or boundaries.

3.1 IRENA grid assessment studies

The feasibility of attaining up to 90% renewable penetration through a combination of solar, wind, hydropower and biogas was demonstrated in a study conducted in Upolu (Samoa). This ambitious scenario emphasised the critical importance of energy storage for frequency regulation, advanced inverters that can provide grid support, and proactive management of reactive power (IRENA, 2015a).

The analysis of Palau indicated that the current system could accommodate a substantial amount of solar PV power (up to 30%) without causing significant operational disruptions. The deployment of enabling technologies and a meticulous economic analysis would be required to surpass this threshold. Options for enabling technologies and operational measures include strategic curtailment mechanisms to balance the system, targeted demand-side management (DSM) initiatives, or energy storage to mitigate excess generation (IRENA, 2013).

The grid assessment for Aitutaki (Cook Islands) explored the feasibility of utility-scale solar PV power. It underscored the importance of strategies to manage instantaneous VRE penetration levels. Its recommendations included integrating energy storage solutions like batteries, optimising the dispatch of conventional generators alongside solar, refining frequency control settings, and ensuring that solar inverters provide essential grid-forming functionalities (IRENA, 2015b).

In the Dominican Republic, IRENA conducted a techno-economic analysis to quantify the impacts of operating the country's power system with increasing shares of wind and solar PV power in the years between 2020 to 2030. The Dominican grid, according to the study, could achieve an instantaneous penetration of 63% VRE generation, reduce carbon dioxide emissions and reduce the cost of electricity generation by applying advanced forecasting. The study revealed that the integration of VRE could introduce frequency stability, congestion and voltage issues, which could be overcome by installing storage systems for frequency support, obligating grid support functionalities from VRE generators, implementing reactive power compensation, upgrading the grid infrastructure, and modifying the grid code (IRENA, 2020).

For the island of Viti Levu, IRENA supported the government of Fiji to identify a pathway to tap into its solar PV potential. Assessing both the distribution feeder level and the system level analysis provided insights into how 25 megawatts (MW) of utility-scale solar PV power and 40 MW of distributed solar PV power could be included in the system without making significant investments in overcoming the constraints introduced that power. The recommendations for managing the constraints to system operation included modifying the grid code, adapting reserve requirements and modifying a few operational practices (IRENA, 2018a).

At the request of the Government of Vanuatu, IRENA evaluated different techno-economic options on Espiritu Santo to increase the share of renewables, including wind, solar PV and hydro power as well as biofuels, in the Luganville grid to achieve 100% generation from renewables. It was evaluated that a 98% share of instantaneous demand in Luganville could be met by renewables by upgrading the system, developing a detailed grid code, implementing battery storage systems, implementing a comprehensive control system, dynamically managing spinning reserve, implementing better monitoring for renewable resources, and deploying more hydropower generation, subject to availability of grant funding (IRENA, 2019a).

In Antigua, IRENA conducted a technical study to evaluate the technical constraints to optimising the shares of renewables while maintaining the stability and reliability of the system. The generation expansion plan of solar PV and wind power was found feasible, even under critical scenarios of low demand coinciding with high VRE generation. The challenges highlighted included an increased risk of voltage or frequency collapse, reduced system inertia, complexity in the calculation of unit commitment and optimal dispatch. The recommended solutions included a comprehensive control system, grid-supporting functions from VRE, installation of distributed PVs based on the feeder rating, modification of protection system settings, and an updated spinning reserve calculation process (IRENA, 2015c). The Republic of the Seychelles is actively pursuing a sustainable low carbon future and hopes to achieve the e-mobility targets established in its NDCs. IRENA provided a grid impact assessment for the use of EVs in the low voltage grid. Finalised in 2025, the study highlighted the need for upgrading feeders with low hosting capacity for EVs and deploying smart charging strategies, combined with rooftop solar PV and behind-the-meter battery storage to reduce stress on the system. It also highlighted the need to introduce market mechanisms and regulations, and to modify grid codes to prepare for EV inclusion. This report synthesises the insights from past studies to chart a clear roadmap for SIDS stakeholders. It offers tailored recommendations and actionable implementation strategies, providing strategic guidance throughout the grid modernisation journey.

3.2 Challenges identified by IRENA studies

IRENA's comprehensive assessments across diverse SIDS highlight some core challenges SIDS face in the inclusion of renewable generation. These challenges include:

- **Stability concerns with high VRE:** One of the key issues that small power systems face is the regulation of frequency and voltage. The limited inertia characteristic to smaller island systems, due to lower number of synchronous generation units, can amplify stability issues, particularly frequency stability, as the share of solar and wind generation increases. Studies emphasise the need for advanced control mechanisms, storage solutions and grid-forming inverters to mitigate these risks and ensure system reliability.
- **Limitations of legacy infrastructure:** Existing generation and grid control systems often lack the flexibility and grid support capabilities necessary for seamless VRE integration. Existing thermal generation units that are used to generate spinning reserves must operate at their technical minimum, which is typically around 60%. Consequently, they are unable to operate at "zero" dispatch. This leaves less room for the renewable generation, which therefore is curtailed, leading to reduced revenues. The installation of new renewable generation capacity may require grid upgrading or grid reinforcements to avoid overloads of lines, voltage problems, curtailment, and so on. Upgrading or retrofitting conventional generation, alongside broader system modernisation, which includes the capability to monitor and control the various devices connected to the network, is a critical element for a successful transition.
- **Regulatory and market barriers:** Outdated regulatory frameworks, tariff structures, and a lack of enabling policies can impede the deployment of distributed energy resources (DERs). Administrative bottlenecks and the lack of a transparent and supportive regulatory environment are critical challenges. The lack of grid codes in most SIDS stands out as one major constraint to operating the system efficiently with VRE. On certain islands, grid connection requirements for renewable energy projects are adopted from neighbouring systems, and they may be excessively stringent. In most cases there are no explicit reference to new enabling technologies, such as storage, and the connection requirements for self-consumption. Targeted regulatory reforms, updated standards and market-based solutions alongside purely technical grid considerations are also important.
- **Technical capacity:** The ability to identify DER deployment needs and sector coupling opportunities, as well as to conduct proactive planning, are critical components of achieving a holistic transition. For the effective use and deployment of these resources, and to ensure their absorption and future scaling up, local expertise needs to be further developed.

3.3 Recommendations from IRENA studies

Collectively, the IRENA studies highlighted the need for customised grid modernisation strategies tailored to the specific energy mix, load profiles and geographic constraints of SIDS. The studies consistently point towards the pivotal role of emerging technologies like energy storage, advanced control systems, grid codes, advanced inverters, and demand-side flexibility in unlocking the full potential of renewable energy on island grids.

- **Reinforcing the grid:** The presence of grid-connected prosumers (users who both generate and consume) may lead to bidirectional power flow in a grid designed to have unidirectional flow. It may be necessary to install new lines to transfer the electricity generated from newly installed VRE capacities. This will challenge protective system settings, cause frequent cycling of transformers impacting their lifespans, and lead to potential overloading. Smart transformers, intelligent grid management solutions and infrastructure upgrades can effectively respond with the variability introduced by DERs.
- **Smarter operational measures:** To improve the frequency stability of island power systems, measures relating to operation, control and protection could be implemented. The response of a power system after a generation-load imbalance mainly depends on the size of the disturbance, the system's inertia, and the response speed of the primary frequency control. Reviewing generation droop settings, retrofitting existing conventional generation units to include primary frequency control, implementing under-frequency load shedding (UFLS) schemes and modifying protection system settings, such as frequency and voltage protection, to avoid accidental tripping are measures that can be adopted. A minimum number of must-run units could be considered to guarantee that sufficient inertia is available. Increasing the granularity of dispatches to intra-hour with more updated VRE forecasting could also help in reducing reserve requirements and VRE curtailment.
- **Inclusion of enabling technologies:** The review of grid assessment studies has identified several technology enablers to boost the hosting capacity of island power system. Most studies recommend the installation of energy storage systems (ESS) to provide primary frequency control. ESS such as battery energy storage systems (BESS) should provide other grid-supporting functionalities, such as voltage regulation and black-start capability, and should contribute to the mitigation of congestion. Synchronous condensers and FACTS devices such as static synchronous series compensators can be used to control power flows in meshed systems and solve congestion problems. Dump load resistors can also act as flexible dummy loads, providing over-frequency control when combined and co-ordinated with renewable generation. Most studies have concluded that after a certain VRE penetration level, an automatic and centralised control system is necessary to perform unit commitment and generation dispatch, determining the generation set points by minimising system operation costs and guaranteeing security constraints.
- **Developing and modifying grid codes:** Grid codes provide, among other features, rules or guidelines for the operation of the power system, the grid connection of devices, and market regulations. The development of a detailed grid code, when no such grid code exists, and the adoption of technical standards are strongly recommended. Mandating grid supporting functionalities from VRE generation through grid connection requirements is one option available. An example revision in grid codes would include reviewing and updating spinning reserve criteria to cover the outage of individual generation units and reducing the use of UFLS as a kind of negative spinning reserve causing to shed load. Short circuits lead to significant voltage drops, causing inverters to trip. Implementing fault ride-through (FRT) capability in VRE generation and dynamic voltage support from VRE – providing not only voltage control but also the ability to inject reactive power currents – are two recommendations for withstanding these voltage drops and supporting grid recovery.

A detailed discussion on the above point will be provided in chapters 5 and 6.

4 Obstacles to and drivers of renewable integration and grid modernisation in SIDS

On the path towards a modernised and renewable-dominated power system, SIDS face unique constraints that require careful consideration. Modernising grids in SIDS can be challenging due to the associated costs and the logistical challenges involved in transporting new technologies. Limitations with the technical capacity of staff to implement and operate the new technologies adds to these challenges along with impeding innovation and the adoption of complex technologies. Existing market regulations further acts as a challenge to the integration of these energy sources. Another hurdle to the inclusion of renewables is the limited availability of land in SIDS, which can limit the large-scale deployment of renewables and the associated expansion of transmission and distribution systems. The peak demand in SIDS is influenced by weather and tourism, which makes it critical to accommodate distributed resource solutions that are tailor-made for the specific island.

Recent climatic events have prompted investigations into how to incorporate resilience into the energy planning process, particularly in SIDS. The incidence of high-impact, low-frequency weather phenomena is on the rise. Catastrophic events, such as wildfires, cyclones and floods, are causing unprecedented destruction, wiping out whole communities and leaving significant populations without electricity and water due to the devastation of vital infrastructure. That is especially true for least-developed countries and SIDS, which are usually in areas more affected by climate change, such as through rising sea levels, and are more susceptible and vulnerable to severe weather events due to limited resources to be resilient to such events. Though such severe weather events are usually not considered within the purview of network reliability standards, building a more resilient and reliable grid is the need of the hour.

Most SIDS have ageing power systems that require modernisation or upgrades to operate securely with high shares of renewables and DERs. A more conducive environment to attract investment and innovation will ensure that the full potential of grid modernisation can be tapped into. The modernisation of grids cannot be achieved in silo. It is a co-ordinated effort involving stakeholders such as the utilities and the independent power producers, who face challenges because of the complex dynamics of the system. System operators can find the inclusion of renewables, especially VRE and DERs, an unwanted change from status quo. This reluctance to change can manifest in many ways and can slow the progression to a more modernised grid. Bureaucratic hurdles and lobbying efforts add to the already constrained markets and competition. Complicated permitting processes and lengthy authorisation are also challenges for the transition.

4.1 Regulatory barriers

Older or technology-specific grid codes, typically adopted from larger, interconnected systems, offer a significant obstacle to the grid modernisation that SIDS urgently require. These regulations lack consideration for the specificities of island grids or the capabilities of emerging technology. Consequently, they hinder the integration of these technologies, thereby constraining the grid from becoming a key asset in the energy transition.

The lack of grid-supporting functionalities from VRE and the difficulty of withstanding large voltage and frequency variations have been identified as possible problems for maintaining the stability of island power systems. VRE functionalities that can provide both voltage and frequency control, and the ability to ride through voltage and frequency variations, reduce the risk of undesired tripping of generation assets. These functionalities are mandated by grid codes, and therefore there is a need for updated grid codes that specify the connection requirements to the grid. Obsolete regulations can create stringent and expensive requirements for DER connections, complicating the process and discouraging their use.

These regulatory barriers have ripple effects. Investors become wary of projects facing excessive red tape, hindering the flow of vital capital for grid modernisation. Outdated codes perpetuate a technological status quo that reinforces reliance on imported fuels and leaves SIDS trapped in a cycle of economic vulnerability. The inability to harness demand flexibility drives up energy costs, placing strain on businesses and households alike.

4.2 The stability challenge in island grids

An increase in VRE has operational consequences, and power systems must possess the ability to dynamically manage the variability in demand for both active and reactive power. Furthermore, the system must possess the ability to provide electricity that meets a specific set of criteria for frequency, voltage and reliability (Kundur, 1994). The intrinsic unpredictability and uncertainty of VRE sources, such as solar PV and wind, add to the existing variability of demand. VRE sources are often inverter-based resources, which at present do not consistently contribute to frequency and voltage regulation. A secure power system is a system that is stable and can maintain its integrity. The addition of VRE changes the system dynamics, which causes stability to be a limiting factor; therefore, stability studies are of great importance. The most recent classification of power system stability is discussed in Box 2.

Traditionally, power systems have relied on the rotational inertia of synchronous generators, of diesel or fossil fuel plants or of hydropower generation units to maintain grid stability. Inertia from rotating machines acts as a buffer, absorbing the initial fluctuations in power demand or generation and ensuring smoother frequency regulation to a stable value. It helps reduce the rate of change of frequency (RoCoF). Larger RoCoF values indicate a faster decline of frequency to a frequency nadir that can activate under-frequency protection devices. The absence of synchronous generation units in island systems with high VRE, and therefore a lack of inertia, makes these systems particularly susceptible to frequency instability. Frequency stability is the power system's ability to maintain a steady frequency following disturbances and when there is an imbalance between generation and demand. In small, isolated grids, even minor fluctuations can have disproportionate and rapid impacts, potentially leading to cascading failures and widespread blackouts. To improve the frequency stability of island power systems, measures relating to operation, control and protection system could be taken. Advanced inverters capable of providing synthetic inertia, fast-response ESS, and synchronous condensers will play a crucial role in maintaining stable grids in a renewable-dominated future. Addressing this challenge effectively demands a systemic evaluation, proactive policy mechanisms, targeted investments and collaborative knowledge sharing to ensure that the transition to clean energy does not compromise the overall reliability and resilience of island power systems.

4.3 Operational complexities

Operational complexities emerge from the specific characteristics of SIDS power systems. Traditionally designed for unidirectional power flow, the inclusion of grid-connected DERs, such as rooftop solar PV, storage and EVs can cause issues to protection settings, voltage variations and potential overloading which could lead to instability in the grid. SIDS power systems are characterised by limited monitoring and controllability, which leaves the system operator with a not-so accurate picture of the real-time status of the grid, even leading to needing curtailment of VRE. The lack of forecasting capability for either demand and/or VRE impedes proactive grid management and optimal use of resources.

4.4 Market structure limitations and managing stakeholder interests in SIDS

Although strong political leadership and commitment to the energy transition, as well as appropriate institutional frameworks and dedicated agencies, have been established in most SIDS, lack of regulatory oversight from independent regulatory agencies challenge the deployment of renewables. Lack of regulatory oversight creates space for undue influence from parties who may want to slow the transition, detracting from the greater good for consumers. The structure of the electricity sector, as in being vertically integrated or unbundled, and the lack of a power market with regulations adapted to the SIDS context, affects the ability of the power system to accommodate high VRE shares.

Scarcity of skilled technical capacity and the issue of land availability are also challenges that impede the permitting and deployment of renewable energy projects. Building technical capacity in SIDS is therefore essential for the energy transition to occur. It is also necessary to identify and share information on areas that are suitable and available for the development of renewable energy projects. An additional obstacle is the absence of community and consumer engagement in these projects, which frequently results in a lack of awareness of a project's advantages. Grid development plans must be aligned with a country's ambitious objectives and must involve a broader range of stakeholders, necessitating improved collaboration and information sharing among them.

4.5 Impact of extreme weather events

The performance of a power system is fundamentally characterised by the concepts of resilience and reliability, which are frequently confused. Reliability is the system's ability to operate satisfactorily; resilience is the system's ability to withstand and re-establish acceptable levels of operation in the face of an extreme event. Resilience also referrs to the capacity of a power system to anticipate extraordinary and high-impact, low-probability events, recover rapidly from these disruptive events, and improve its operation and structure in anticipation of similar events in the future. In addition to mitigating the effects of these events, resilient infrastructure should also be capable of enabling rapid recovery.

A power system's exposure to an extreme event is contingent on the extent to which it is situated in hazard-prone areas and can be identified once the magnitude, duration and area affected by the natural hazards is assessed. These hazards can have a significant impact on power systems, rendering them more vulnerable to physical damage. In addition to the substantial direct economic losses that arise from outages, hazards have detrimental effects on socio-economic development.

All power system segments are at risk of being affected by extreme events. The system is susceptible not only to volatile fuel costs but also to disruptions in the fuel supply chain, to water availability, and to the infrastructure through which the fuel is delivered, if the system is heavily reliant on one generation technology. The oil and gas supply chain is particularly susceptible to storm surges as a result of its reliance on terminal and harbour infrastructure, as well as its reliance on continuous power for its operation. Furthermore, power outages render infrastructure such as pipelines, oil terminals, storage tanks and filling stations inoperable. When diesel generators are employed to provide backup electricity and/or critical services, such as hospitals or communications infrastructure, their on-site fuel supply is frequently restricted, as they are also reliant on transportation infrastructure to maintain operations during extended outages.

The impacts are not limited to conventional generation units. The power generation from wind is directly influenced by variability in wind speeds, solar irradiation and rainfall. Unlike thermal generation assets, wind turbines are not significantly affected by droughts and heatwaves; however, they can be affected by earthquakes or storm events when wind speeds exceed the design limits. The primary vulnerabilities of solar PV systems are high winds and hailstorms, which have the potential to damage the PV modules. Hydropower generation is highly susceptible to drought and seasonal fluctuations in water availability due to its reliance on water as its sole fuel source.

The most apparent extreme weather damage is the flooding of power stations and the destruction of transmission and distribution wires and assets as well as transmission towers and poles. Subsequently, the majority of outages are the result of transmission and distribution system failures, with storm events being the primary source of damage, whether from flying debris, falling trees or the combination of high wind speeds and ice, which causes the lines to break.

While grid evaluation studies do not directly address resilience, they do offer valuable insights into grid problems that can be resolved to enhance it. Potential expansion planning choices encompass investments in infrastructure (*e.g*. placing lines underground, weatherising assets or decentralising renewable energy sources) as well as operational solutions (*e.g*. online monitoring and control systems).

5 Technology and infrastructure toolkit for SIDS grid resilience

The inherent geographic and economic characteristics of SIDS create vulnerabilities, yet SIDS possess the potential to become global leaders in sustainable energy innovation. Grid upgrades, such as infrastructure reinforcements, energy storage, advanced monitoring systems and grid-enhancing measures, must be prioritised for their potential to maximise the benefits of renewable integration. Unlocking demand-side flexibility through smart technologies and targeted programmes will empower consumers to actively shape their energy use, aligning it with renewable generation patterns and reducing the need for costly backup generation. Grid-forming DERs, capable of mimicking the stabilising properties of conventional generators, offer a vital solution for maintaining stable operation in island grids with high renewable penetration. Furthermore, SIDS can generate new revenue streams by enabling the operation of new and emerging ancillary service markets, such as stability markets. These mechanisms financially reward assets capable of providing grid-supporting capabilities, incentivising the integration of DERs and bolstering the overall resilience of the power system.

5.1 Targeted infrastructure upgrades

Strategic grid upgrades, tailored to the unique circumstances of SIDS, play a pivotal role in accelerating grid modernisation. Prioritisation is essential. Targeted grid upgrades can alleviate bottlenecks to evacuating power generated by renewable resources. Such upgrades include the deployment of advanced monitoring and control systems for real-time monitoring and visibility of the grid. This will allow better controllability of DERs, such as storage and rooftop solar PVs, adding to the resilience of the system. Robust communication and smart metering infrastructure can allow optimal DER management and consumer participation. FACTS and other compensating devices can be installed to provide grid-supporting functionalities on reactive power regulation and improved flexibility.

5.1.1 Grid reinforcement for energy resilience

SIDS often require reinforcements to accommodate the power from new generation units without compromising reliability. The siting of renewable plants is usually planned on sites with access to grid connection. If not, then grid connection upgrades are essential for for evacuating power, preventing transmission/distribution line overloads and reducing curtailment of generation. System adequacy is an indicator of specific reinforcement requirements. Investing in measures that alleviate congestion, such as adding parallel lines, upgrading substations and transformers, or deploying advanced power flow control technologies, plays a vital role in maintaining grid stability.

Energy management systems (EMS) are an example of advanced technologies that can be implemented in island systems to enhance system operation with higher shares of renewables. The island of Aruba[1] has implemented

1 Kingdom of the Netherlands.

an intelligent generation management system and an intelligent load shedding system to mitigate extended power interruptions, maintain a stable power supply, and expedite response to power demand imbalances or interruptions.

Streamlined permitting processes, clarity on feasibility studies, use of technical standards, and transparent approval procedures are vital to encourage investment in renewables and grid reinforcement. In addition, infrastructure projects must be implemented with the utmost sensitivity towards fragile island ecosystems, adhering to rigorous environmental impact assessments and sustainable construction practices. Additional considerations include exploring modular technologies, prioritising upgrades that maximise impact, and engaging stakeholders for buy-in and smooth project execution.

5.1.2 Role of technical standards

Grid codes describe the expected behaviour from generating units and other system users, when connected to the grid and enforce industry standards. Product specification standards are guidelines or best practices and technical benchmarks for the design, installation and commissioning of equipment, important in achieving performance, safety, and reliability. While technical standards provide guidelines to ensure that quality and safety are maintained when choosing different technical devices, grid codes are the legal framework that translate these standards into actionable and mandatory requirements. As systems evolve, standards are updated, and these are incorporated into grid codes. Grid codes and standards have bidirectional relationship as system specific requirements may result in modifications in standards and vice versa. Table 3 highlights a non-exhaustive list of technical standards that can be referred to for the design, installation and commissioning of technical equipment (IRENA, 2022).

Table 3 IEC and IEEE product specification standards relevant to power systems and variable renewable energy

Standard	Content	Standard	Content
IEC 60034	Rotating electrical machinery	IEC 61215	Terrestrial PV systems
IEC 60044	Instrument transformers	IEC 61400	Wind turbine design
IEC 60045	Steam turbines	IEC 61730	Construction of PV systems
IEC 60076	Power transformers	IEC 61868	Insulating mineral oils
IEC 601143	Series capacitors for power systems	IEC 61869	Instrument transformers
IEC 60044	Voltage and current transformers	IEC 62052	Electricity metering equiptment
IEC 60308	Hydraulic turbines	IEC 62548	Solar PV arrays
IEC 60358	Coupling capacitors	IEC 62934	Grid integration of renewable generation
IEC 62052	Electricity metering equiptment	IEEE 112	Induction motors
IEC 62053	Static meters for AC active energy	IEEE 115	Synchronous machines

IEC 60076	Power transformers	IEEE 421	Synchronous machines
IEC TS 61836	Solar PV energy systems	IEEE 929	Solar PVs

Source: (IRENA, 2022).

Notes: IEC = International Electrotechnical Commission; IEEE = Institute of Electrical and Electronics Engineers; PV = photovoltaic.

The IEEE 1547 series of standards addresses the issue of ensuring a technically sound interconnection of DERs. Interconnection standards have a much closer relationship to technical requirements and power system operation. IEEE 1547-2018 highlights technical specifications for, and testing of, the interconnection and interoperability between utility power systems and DERs. It is technologically agnostic and applicable to synchronous generators or non-synchronous generation based on inverters alike. The focus is on the interconnection of DERs to high-, medium- and low-voltage distribution systems. It is the standard for inverter certification and is extensively used for grid connectivity, offering guidelines for assessing inverter compliance criteria. IEEE 1547-2018 also governs electric vehicle (EV) safety and functioning.

IEEE P.2800 establishes the minimum requirements, characteristics and performance of inverter-based resources for interconnecting with transmission and sub-transmission systems. Its requirements relate to, among other things, voltage and frequency ride-through, active power control, reactive power control, and system protection.

In general, standards are non-legally binding (although compliance with standards can be mandated by law; for example, the Mauritius grid code mandates compliance with the IEC 61000 series on power quality, among others). Grid codes, however, are legally binding. For instance, IEEE 1547-2018 is mandated in Mauritius for grid-connected PV systems. Similarly, IEEE 1547-2018 applies in Antigua and Barbuda, where each generating facility generator must be in conformance with the standard for interconnection to the network. In Antigua, IEEE standard conformance test procedures and the use of UL 1741 inverters, converters and controllers is recommended.

Table 4 highlights some of the interconnection standards that SIDS can use to define their grid codes

Table 4 International interconnection standard

Standard	Content
IEC 62257	Microgrids
IEC 62786	DER interconnection with the grid
IEEE 1547-2018	Interconnecting distributed resources with electrical power systems
IEEE P.2800*	Connection of IBR to bulk energy systems (transmission)
EN 50549	Interconnection for generators up to Type B according to the EU Network Codes RfG, including EU NC RfG compliance certification

Source: (IRENA, 2022).

Notes: DER = distributed energy resource; EU = European Union; IEC = International Electrotechnical Commission; IEEE = Institute of Electrical and Electronics Engineers; NC = network code; RfG = requirement for generators.

5.1.3 Energy storage systems

ESS, particularly BESS, hold immense potential to accelerate grid modernisation and the inclusion of VRE in SIDS power systems. Numerous studies highlight the role of ESS in providing primary frequency control, a critical service traditionally supplied by conventional generators (IRENA, 2015b, 2015c, 2015a, 2019a). This ability to rapidly adjust power output in response to system disturbances is critical for maintaining stability in the face of increasing renewable power penetration.

Beyond frequency control, BESS offer a suite of grid-supporting functions that are particularly valuable for SIDS (IRENA, 2019b). By storing power during periods of excess generation and discharging during peak demand or outages, BESS can mitigate congestion (IRENA, 2019c), reduce reliance on costly fossil backup generation, and enhance overall grid resilience. Storage can also cover reserve requirements if designed to do so. BESS can be classified based on their capacity and application as either behind-the-meter batteries or utility-scale batteries.

While batteries are mature technologies, other ESS technologies like flywheels can provide a rapid surge of power to support frequency regulation (IRENA, 2013, 2016a). SIDS, depending on the terrain and resource availability, can also exploit the possibility of pumped hydropower storage systems. The Faroe Islands, in Europe, has high wind power generation especially during the winter season and, due to the suitable terrain, is investigating the possibility of implementing a pumped hydro storage system to store excess wind power (SEV, 2025). Integrating flexible, controllable loads can further support frequency regulation (IRENA, 2019a). By exploring these complementary technologies and strategies, SIDS can optimise their investments and build a robust and multifunctional energy storage infrastructure that underpins a reliable and sustainable energy future.

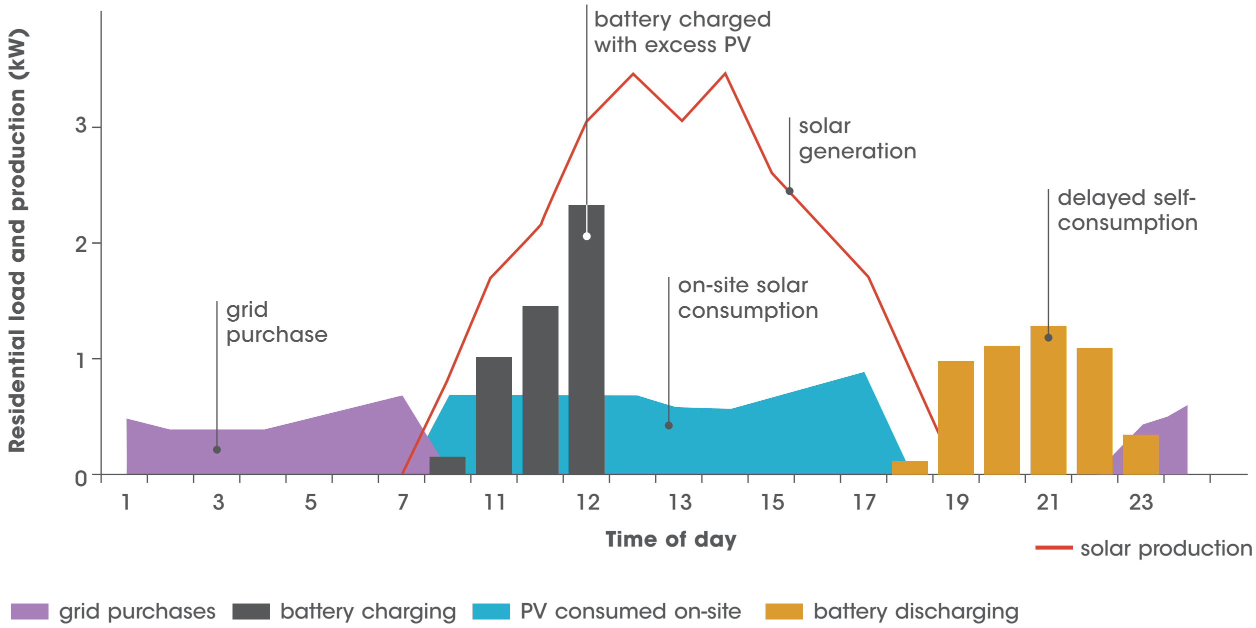
The primary source of energy on the Caribbean island of Aruba, which has a peak demand of 155 MW, is imported heavy oil. Renewable resources, including solar and wind, account for 19% of the total generation. Included in the Aruba storage system are flywheels, which have a storage capacity of 5 MW for 12 minutes, as well as batteries, which are currently in the implementation phase (EU, 2023). These projects play a crucial role in maintaining the stability and efficiency of the grid, and the underground flywheels are expected to serve renewable capacity firming and resiliency.

Behind-the-meter BESS for island energy optimisation

Behind-the-meter BESS are essentially small-scale BESS, ranging usually between 3 kilowatts (kW) at residential scale and 5 MW at commercial or industrial scale customers, and connected to consumer meters, and enables demand side flexibility, thus helping to integrate higher shares of renewables (IRENA, 2019c, 2019b). The main driver for small-scale BESS together with behind-the-meter VRE generation (*e.g.* rooftop solar PVs) among consumers has been the reduction of electricity bills by optimising energy consumption from the grid. For instance, the electricity tariff in Spain has a term related to energy consumption and a term related to contracted maximum capacity, which can be both reduced by BESS.

The behind-the-meter batteries can store power from the rooftop solar PVs and/or from the grid as and when electricity prices are low. Figure 8 exemplifies a case where the BESS charge with excess PV production in the late morning hours, which is then discharged in the evening, reducing energy consumption from the grid during peak hours (IRENA, 2019b). The BESS can provide backup support and improve resilience to blackouts when they have appropriate control schemes. They can also offer voltage and frequency support and defer investments in the traditional grid, with the right inverter control implemented. The uptake of BESS is also impacted by the right regulatory framework, such as time-of-use tariffs and net billing. Reducing upfront costs and soft costs such as connection and permitting costs can support the uptake of behind-the-meter batteries (IRENA, 2019b).

Figure 8 Typical solar PV production and battery charging/discharging schedule

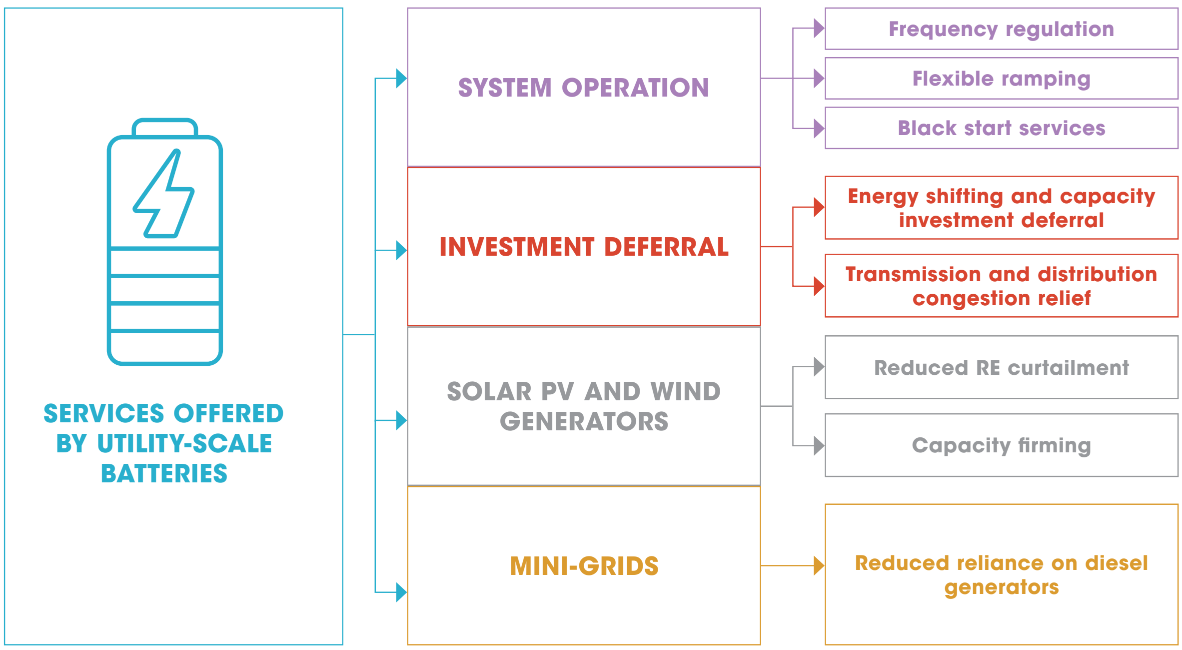


Source: (IRENA, 2019b).

Note: kW = kilowatts; PV = photovoltaic.

The main services that behind-the-meter BESS can provide have been outlined by IRENA in Innovation landscape brief: Behind-the-meter batteries (IRENA, 2019b).

Figure 9 Services offered by utility-scale battery storage systems



Source: (IRENA, 2019d, 2019c).

Notes: PV = photovoltaic; RE = renewable energy.

Maximising utility-scale BESS value in SIDS

The key services that utility-scale batteries can provide can be grouped into four families: system operation, investment deferral, renewable integration, and mini-grids, as shown in Figure 9 (IRENA, 2019c). Flexible, multi-tasking of batteries needs to be explored to make them economically viable.

System operation-related services that can be provided by utility-scale BESS include frequency response, ramp rate control, black start and regulation reserves. The provision of black-start services is contingent on the capability of the BESS to function in grid-forming mode. Except for short-term frequency control, the energy capacity of BESS must be adequately high to provide black-start services. Utility-scale BESS can support investment deferral, energy shifting and congestion relief. BESS can provide capacity reserves by shifting energy and therefore replace peak generators. The system operator can control the BESS directly according to the given regulations. VRE generation-related services include the reduction of VRE curtailment and capacity firming. Curtailment is reduced when excess generation from VRE can be stored and used at another time, or it can be used as a short-term reserve. The ability of BESS to smooth the output of VRE sources and control the ramp rate is referred to as capacity firming.

Mini-grids with batteries can help reduce dependency on diesel generators. Mini-grid systems have typically relied on diesel generators for reliable energy supply. BESS can act as backup and help balance the supply and demand by charging and discharging as needed. Long-term planning should consider the provision of flexibility and other services from BESS, and regulatory frameworks should be developed that ensure the economic viability of BESS through new revenue streams from participation in ancillary services.

5.1.4 Flexible AC transmission systems

FACTS are advanced power electronics technologies that can support SIDS in their renewable energy integration. They can regulate power flows dynamically and provide reactive power compensation to improve voltage profile, stability and power quality. They can support the deferment of grid upgrades by reducing congestion. The most common FACTS technologies are static volt-ampere reactive (VAR) compensators and static synchronous compensators (IRENA, 2018b). The deployment of FACTS can be based on a cost-benefit analysis that considers the economic and operational challenges that FACTS can help resolve. FACTS can support the optimisation of existing infrastructure and assets, thereby helping to defer grid upgrades. They can also contribute to strengthening the grid and controllability of the grid, helping to manage the variability of the VRE.

5.1.5 Smart metering

Smart meters are digital meters that detects the electricity fed to the grid or consumed from the grid by a prosumer. It provides detailed insights into the consumption patterns and enables better monitoring of the grid. The deployment of smart meters can provide a more accurate picture of the system state to the system operators and is an essential component of smart grids. In other words, smart meters can improve the observability of the power system and also offer insights into improving energy efficiency. The emergence of smart meters, together with other technologies for data analysis and grid automation, offers new and efficient ways of network management, such as automated voltage control or automatic grid reconfiguration. Typically, the vast volume of data collected from all smart meters is managed in data hubs. The smart meter device serves as the foundation for observability and controllability solutions that use distributed power generation and flexible demand.

5.1.6 Real-time data and analytics-advanced forecasting for improved island grid operations

The critical issue with VRE integration impacting the planning, operation and control of power systems can be to some extent mitigated by improving VRE forecasts, by updating the underlying forecast methodology and data. Advanced forecasting can predict generation output on a two- to six-hour interval quite accurately in average terms. Today, the hour-ahead forecast errors of a renewable generator typically range from 3% to 6% of its rated capacity and the day-ahead forecast errors at regional levels range from 6% to 8% (NREL, 2015). The longer the forecast time horizon and the smaller the forecast region, the larger the forecast errors. The use of real-time data and large sets of historical data, as well as the application of data mining techniques, can lead to improved forecasts.

For instance, the EWeLiNE project uses real-time data from solar panels and wind turbines around Germany and processes them using machine-learning techniques to estimate the renewable energy output for the next two days (Fraunhofer, 2016; IRENA, 2019d).

The Philippine grid code imposes minimum requirement for system wide renewable energy source forecasts as well as for individual units renewable energy generation forecasts. Table 5 shows the performance requirements for individual renewable energy generation in the Philippines (Energy Regulatory Commission, 2016a). Over time, the requirements become stricter. Requirements for run-of-river generation are stricter.

Table 5 Philippine grid code requirements for forecast performance (Energy Regulatory Commission, 2016a)

Required performance	Years after renewable energy generation commitment	
	First and second	Third and subsequent
Periodicity of updates	1 hour	1 hour
Forecasting periods	1 hour	30 minutes
Forecasting errors: mean absolute error (%); P95 error (%)		
Short-term forecast (0-4 hours)	< 10; 15	< 5; 12
Medium-term forecast (4-36 hours)	< 25; 35	< 20; 30

5.1.7 Improving grid monitoring using technology advancements

Supervisory control and data acquisition (SCADA) systems, widely used in SIDS, can be upgraded to enable the full realisation of grid modernisation benefits. Upgrading these systems to include advanced EMS or distribution management systems (DMS) is a strategic measure for SIDS. SCADA is a combination of telemetry and data acquisition. It begins with the measurement of data and data collection via intelligent electronic devices. The data from these devices are communicated to the master station and processed using control algorithms and control actions transmitted back to the field in real time. SCADA enables power system operators to perform essential tasks – such as monitoring, collecting and processing data in real time and interacting directly with devices, such as power generators, protection equipment, sensors and motors – through hardware and software components (including human-machine interface software) and recording all events in a log file for further analysis, if necessary.

While SCADA enables supervision and direct control, the EMS is capable of optimising the energy production and consumption as well as storage. It can analyse data including forecasts to make strategic decisions such as charging batteries based on energy prices. After a certain VRE penetration level, an automatic and centralised control system is necessary to perform unit commitment and generation dispatch, determining generation set points by minimising system operation costs and guaranteeing security constraints. All or at least larger renewable energy plants should be connected to and under control of the EMS. In addition to an automatic and centralised EMS, an automatic generation control should be implemented to substitute the manual operation. Power set point control through automatic generation control, also known as a power management system, is also an option. The implementation of SCADA systems with inbuilt EMS and power management systems can also be considered

Advanced DMS platforms offer a suite of advanced functionalities that can be tailored to optimise and efficiently operate the grid with reduced downtime. These systems provide enhanced real-time monitoring, advanced control algorithms and powerful optimisation capabilities. They enable operators to proactively manage power flows, optimise renewable integration and DERs, and rapidly respond to system disturbances, ensuring reliable and efficient power delivery in the face of increasing renewable penetration. Furthermore, EMS, DMS or advanced DMS tools often incorporate cutting-edge communication and data analytics capabilities allowing for the seamless integration of DERs, the implementation of demand response programmes, and the development of predictive maintenance strategies. By adopting EMS or ADMS, SIDS can optimise asset utilisation and enhance overall grid resilience. Distributed energy resource management systems (DERMS) and virtual power plants (VPPs) are technology solutions that can provide better efficiency and flexibility, thereby improving reliability.

Phasor measurement units (PMUs) are another innovation that can capture time-synchronised power system phasors or variables using GPS-enabled time stamping. These units are placed at strategic locations to take measurements, which can form the basis of monitoring and controlling actions over a wider area. The measurements, also known as synchrophasors, can include current and voltage magnitude and phase, frequency, RoCoF, power and harmonics at selected stations, sampled at 10-60 samples per cycle. These measurements allow the comparison of system states, enable conclusions to be drawn about the system and prompt actions to prevent the system from going into blackout.

Mauritius is an example of the application of this technology. The country has adopted a “grid-smartening” approach to encourage increased VRE penetration while still ensuring grid stability and security. With the increasing incorporation of VRE sources into Mauritius’s energy mix, it has become necessary to continuously match the total power generation with the demand and maintain the frequency within safe operating limits to ensure power quality and safe grid operation. PMUs and wide area measurement systems software were installed at five locations (Fort George, Belle Vue, FUEL, Henrietta and Combo substations) to store continuous real-time data on the dynamic performance of the power system (Ministry of Energy and Public Utilities, 2022). Key technologies such as advanced energy and DMS as well as automated distribution feeder and metering infrastructure, have been identified for the smart grid programme.

Artificial intelligence (AI) can potentially improve the performance of power systems. Application of AI to minimise losses, as well as to provide fault managment and condition monitoring, are being piloted. VPPs and DERMs are other tools that can enable grid flexibility. While advanced DMS work to monitor the grid for maintenance purposes and can perform outage management, DERMS are software platforms with real-time communication that can handle the interaction between different DERs and their contributions to markets, ensuring real-time control, co-ordination and optimisation of DERs. VPPs are a system that aggregates behind-the-meter DERs together in a software-based platform to ensure an optimal dispatch of DERs and their participation in markets (IRENA, 2019e). Advanced VPPs can potentially use AI to achieve efficiency, security and reliability. While VPPs ensure co-ordination at a system level, for the provision of flexibility, demand response and frequency regulation that considers generation and demand, DERMs control the devices at the local level, controlling the power and voltage along the feeders. This is done by controlling the voltage regulators, smart inverters, customer loads, on-load tap changers, and so on.

5.1.8 Synchronous condensers for grid stability

Synchronous condensers (SCs) offer a promising solution to the critical challenge of stability in island grids. Essentially synchronous motors running without a prime mover, synchronous condensers provide a rotating mass that contributes to system inertia. Synchronous condensers enhance voltage stability and increase short circuit capacity, improving the grid's ability to withstand faults. Since it includes an excitation system with an automatic voltage controller, a synchronous condenser contributes to voltage and reactive power control. Moreover, it can provide significant short circuit current independent of its control system, and the response is instantaneous.

Instead of installing new synchronous condensers, existing synchronous generators can be retrofitted or repurposed. Repurposing can be either applied within a post-retirement scheme, giving a second life to already retired synchronous generators (Masood *et al*., 2016), or before retirement to synchronous generators planning to cease operation. Although this retrofitting offers a cost-effective solution, their integration requires careful assessment of factors like operational requirements, and optimal sizing for the specific needs of the island power system. The issues with repurposing existing synchronous generators to synchronous condensers can be classified as operational (*e.g*. a starting-up means, like a pony motor, is needed), electrical (*e.g*. insulation and winding conditions must be assessed), mechanical (*e.g*. disconnection of the turbine or use of a clutch; a thrust bearing must be installed if turbine is decoupled), civil (*e.g*. foundation conditions need to be assessed), and commercial (*e.g*. costs of repurposing and costs of operation including active power consumption). Hydroelectric generators seem to be relatively easy to convert, whereas steam turbine generators require a case-by-case assessment (DigSILENT PowerFactory, 2023). Box 3 showcases a practical example of the use of synchronous condensers to improve the integration of wind power, an example from the Faroe Islands (Tróndheim, 2022; Tróndheim, *et al*., 2022).

Box 3 Faroe Island: An example for battery and synchronous condenser application (Tróndheim *et al.*, 2022; Tróndheim, 2022)

The Faroe Islands are a group of 18 islands in the North Atlantic Ocean. Seven grids of different sizes and levels of complexity make up the Faroese power system. By 2030, the intention is for the system to get all its electricity from renewable sources. This is initially being tried on Suðuroy, the southernmost of the islands. As of now, about 46% of Suðuroy's power comes from renewable sources. This includes a 6.3 MW wind power plant, 3 MW of hydropower, 0.26 MW of solar PV, and 13 MW of heavy fuel oil-based generation. The load on the island averages 4 MW, with a peak of 8 MW. The frequency limits of the system lie between 49.5 hertz (Hz) and 50.5 Hz. The wind power plant can be controlled by active and reactive power settings from the dispatch centre.

The island runs frequently on 100% instantaneous wind power and is supported by a battery of 7.5 MW/7.5 megawatt-hour capacity and a synchronous condenser (SC) of 8 megavolt-amperes. The battery has been sized to supply the island for an hour, which gives sufficient time for the heavy fuel oil generation units to come online or the supply to revert from wind, in the event of a sudden change in wind speed or direction. The SC has been sized to contribute to the same short circuit current rating as the thermal generation, especially during peak load.

During periods of wind power fluctuations and when the thermal generating units are deactivated, the battery provides both active and reactive power to the system. The SC also fulfils the function of offering inertial support in the event of a hydropower-generating station outage, thereby assisting in restoring the frequency to its nominal value, in conjunction with the battery. The battery's contribution becomes even more significant when wind power generation reaches zero and the frequency is affected during instances of 100% wind penetration. To meet the demand, the battery is discharged, effectively restoring the frequency to a stable level.

The system operators have seen a significant improvement in wind power use since the installation of the battery and SC and a higher number of days where power generation is only from inverter-based resources. An evaluation of frequency and voltage variations has shown a 33% improvement in frequency variations and a similar improvement in voltage with the help of the battery and SC. It has been seen that it is possible to run the system with 100% inverter-based generation without affecting the stability and security of the system.

5.1.9 Solutions for enhancing resilience

The power system is a complex, interconnected network in which the resilience of individual assets, components or subsystems cannot be simply aggregated to determine the system's overall resilience. The failure of a single component can result in extensive outages and cascading effects. Consequently, it is necessary to employ a comprehensive approach when assessing the resilience of the power system. To facilitate and establish the appropriate regulatory and policy framework, as well as to prevent the implementation of ad hoc and autonomous resilience measures at the individual asset or utility level, a strategic, proactive and long-term power sector plan is required.

Key steps to enhanced resilience include:

- assessing threats and vulnerabilities including hazard identification and classification
- conducting a vulnerability assessment followed by a resilience assessment to assess preparedness and resilience plans
- developing strategies including an emergency management plan and critical infrastructure identification
- identifying resilience-enhancing measures and conducting a cost-benefit analysis of measures

Vulnerability assessment includes identifying weaknesses within existing power systems, including infrastructure, and in operation procedures.

Enhancing the resilience of a power system involves improving damage prevention, recovery and survivability. Solutions that primarily enhance the resilience of the infrastructure (*i.e.* its robustness and resistance to external shock) are typically part of damage prevention. Hardening necessitates the implementation of design standards, siting, inspection, physical security, construction and maintenance. To effectively manage an event as it unfolds and to support a fast recovery of the system requires the rapid assessment of damage and the implementation of preventative and corrective measures. Repair crews are essential during the recovery and restoration phase. Survivability is the ability to provide a minimal level of electricity service to customers in the event that they are unable to access their typical power sources as a result of an extreme event. Operational and planning measures are resilience-building measures that are classified according to the time of the application. Planning measures typically enhance the resilience of the infrastructure by hardening it, whereas operational measures are short term and focus on effective management of the event in real time.

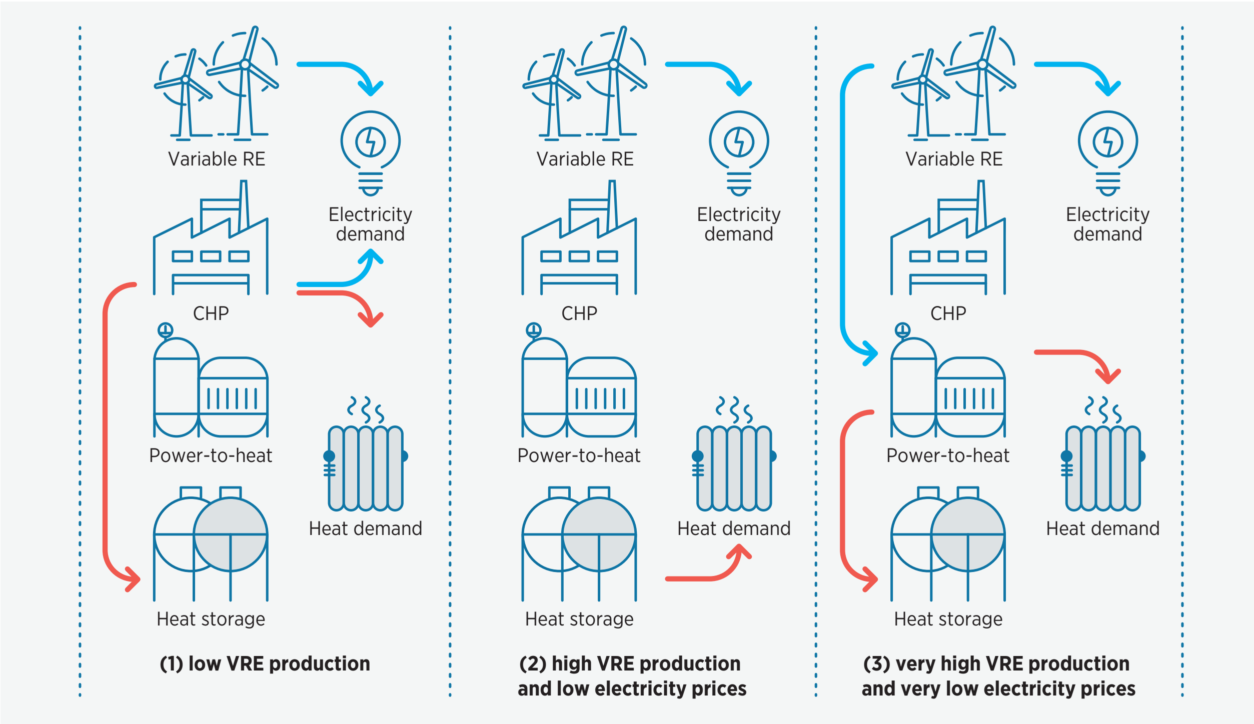
5.2 Power-to-X in SIDS: overview and opportunities

Sector coupling refers to integrating the electric power sector with other sectors such as mobility, gas, and heating and cooling. Sector coupling is also known as power-to-X.

In (Munster *et al.*, 2020), five applications of sector coupling are described: power to residential heating and cooling, power to industrial heating, power to cooling, power to mobility, and power to gas or fuel. Sector coupling arises alongside the electrification of end-consumer use. The existence of an electrification process is thus key to evaluating the potential of, setting up and exploiting sector coupling. The benefits of sector coupling can come in the form of storing energy in different energy carriers (*e.g.* chemical batteries, water, hydrogen), of consuming energy in a different sector, or of transporting energy through a different energy carrier (*e.g.* heat, hydrogen). Consuming energy in another sector is beneficial if the converted energy is cheaper than other sources. Transporting energy through a different carrier, such as hydrogen, can be beneficial since the ratio of energy transported per space required by the transmission infrastructure is smaller.

Figure 10 illustrates the degree of adaptability in connecting the power sector with the heat sector, where the conversion of heat into electricity (through power-to-heat) can help integrate VRE and reduce carbon emissions.

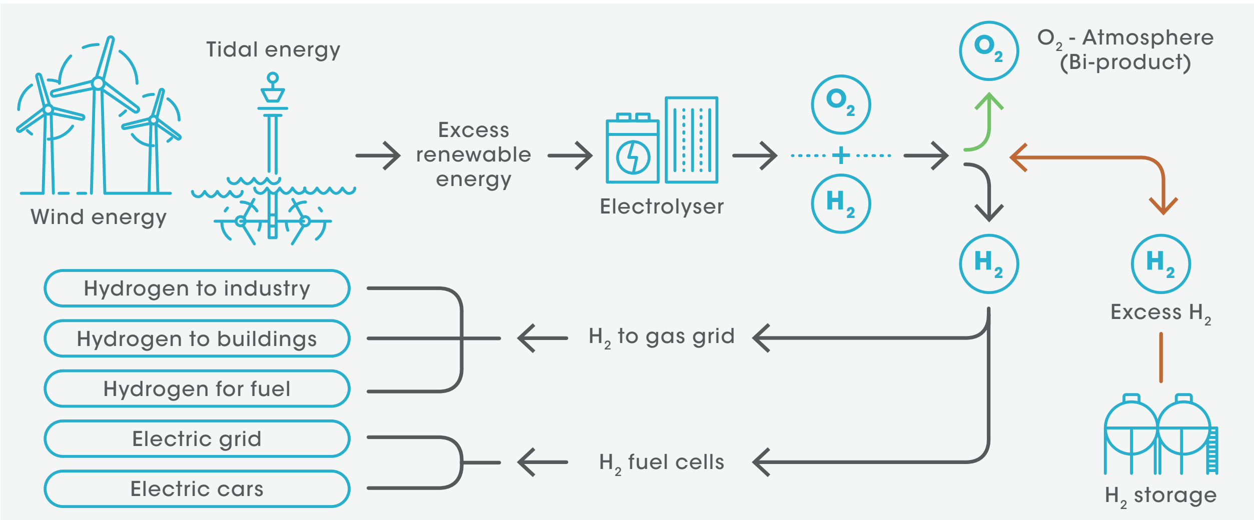
Figure 10 Unlocking the flexibility of district heating



Source: (IRENA, 2019f).

Notes: RE = renewable energy; VRE = variable renewable energy; CHP= combined heat and power.

Figure 11 Structure of the power-to-hydrogen initiative in the island of Orkney, United Kingdom



Source: (IRENA, 2019g).

Notes: H_2 = hydrogen; O_2 = oxygen.

Producing hydrogen to be used for multiple purposes is another way of sector coupling. The island of Eday, Orkney, in the United Kingdom, where the community owns a 900 kW wind turbine, was frequently subject to curtailment as there was a lack of network infrastructure. The community initiated a “surf ‘n’ turf” initiative, which converts excess wind and tidal energy to produce hydrogen via a 500 kW electrolyser (see Figure 11), which is transported via ships to Kirkwall, where it is used. The green hydrogen produced for storage can be used for load shifting or emergency backup and or when the renewable generation is low. Though tidal energy and hydrogen are still in the pilot project phase in Orkney, they are promising additions to the energy transition (IRENA, 2019g).

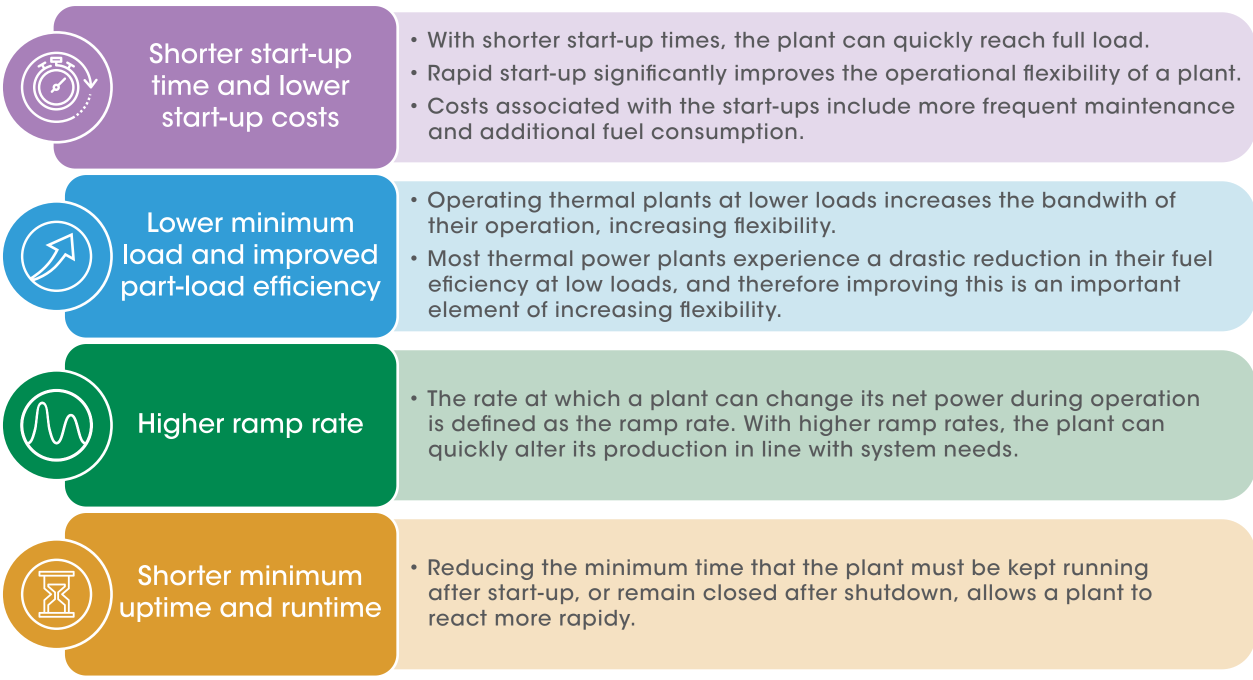
5.3 Unlocking island flexibility

Flexibility is the capacity of the system to match the demand and generation across different time scales, from the short to the long term. This characteristic of the system is a critical factor when incorporating high shares of VRE into the system. Flexibility can be sourced from both the supply side and the demand side. While supply-side flexibility can be sourced from existing conventional generation units, demand-side solutions provide a distinct opportunity for SIDS. EVs and DSM strategies exemplify the potential for sector coupling and unlocking flexibility.

5.3.1 Supply-side flexibility from conventional generation units

Supply-side flexibility can be achieved from new thermal generation or existing units that have been retrofitted to possess improved efficiencies at part load, faster governor response, higher ramping capabilities and shorter start-up periods. These units therefore generally provide a greater amount of headroom for the provision of operating reserves. This solution should not be considered if the objective is to attain 100% renewable targets (IRENA, 2018), but it can help to accommodate solar PV and wind generation variability in the short to medium term.

Figure 12 Flexibility from conventional power plants



Source: (IRENA, 2019h).

Existing conventional units can be refurbished to provide supply-side flexibility through a hybrid arrangement with batteries, or more modern engines, which therefore would reduce reserve requirements (EU, 2023). This is a relatively low-cost solution with a short recovery time. Figure 12 highlights some of the options available to improve flexibility from conventional power plants. Some conventional generators could be retrofitted to include primary frequency control. To further increase reserve availability and additionally reduce renewable energy curtailments, the minimum technical limit of conventional generators can be reduced.

Another operational measure to increase the average VRE penetration level is to enable the possibility to curtail VRE. In some cases, punctually curtailing VRE can be more beneficial than installing less VRE capacity. This solution requires that all, or at least larger, VRE plants be connected to and under the control of an EMS.

5. 3. 2 Electric vehicle integration

The integration of EVs into the grids of SIDS presents significant opportunities to decarbonise the transportation sector while enhancing overall power system flexibility. By incorporating smart-charging infrastructure and advanced controls, EVs in SIDS can act as both loads for renewable energy and as grid-supporting storage devices. Fleets of EVs can act as flexible loads and decentralised storage (IRENA, 2019d, 2019i). Vehicle-to-grid capabilities allow energy stored in EV batteries to be discharged back into the grid during periods of peak demand or can provide ancillary services. This flexibility reduces the need for costly backup generation, often fuelled by imported diesel. Vehicle-to-grid capabilities can reduce transmission and distribution network investments when applying smart-charging strategies.

Indeed, introducing EVs increases demand and operation costs if not accompanied by renewable energy sources, but smart-charging strategies have been shown to provide a significant reduction in operation costs as compared to uncontrolled charging (Sigrist *et al.*, 2017; Taibi and Fernández, 2017). Smart charging adapts the charging to the system and to customer needs and can be pricing based or make use of direct control mechanisms, including unidirectional and bidirectional charging. EVs can engage in demand response programmes, which employ automation and provide incentives for consumer involvement, and therefore present additional opportunities for SIDS. These systems can incentivise consumers to adjust their energy consumption to coincide with periods of high renewable electric generation, thereby optimising the use of the system.

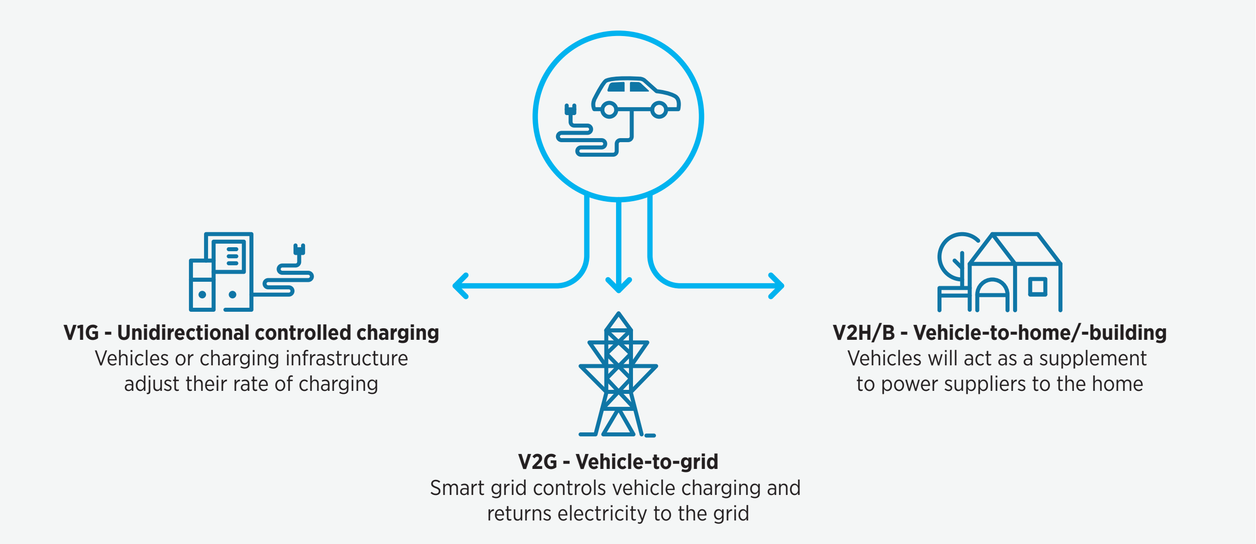
Figure 13 illustrates the different charging mechanisms: unidirectional controlled charging; vehicle-to-grid, including charging and discharging; and vehicle-to-home or building (a particular case of vehicle-to-grid, where charging and discharging are aligned with building needs) (IRENA, 2019d). Further, EVs can provide peak shaving and ancillary services such as reserves. To further unlock their flexibility potential EVs can be aggregated, with new actors and business models in the play. To fully realise these benefits, a strategic approach to EV-charging infrastructure deployment and market design is essential. Robust standards and regulations are crucial for ensuring seamless grid integration of EVs and should include clear guidelines on charger specifications, technical requirements for interoperability across different systems, and robust communication protocols. Some building standards codes require a certain percentage of parking spaces in commercial buildings to include EV charging infrastructure.

Implementing regulations that mandate smart inverters for vehicle-to-grid operations will ensure that EVs can safely and reliably provide grid-supporting services. Equally important is the development of innovative market mechanisms that recognise the value EVs can bring to the grid. Tariff structures that incentivise charging during periods of high renewable generation and that reward vehicle-to-grid capabilities will encourage EV owners to actively participate in optimising grid operations. This market-based approach will accelerate the adoption of EVs and help SIDS reduce reliance on imported fuels, bolster power system resilience and achieve their climate goals.

An IRENA study on the impact of EVs on the low voltage grid of Seychelles in 2025 has shown that unregulated deployment of EV chargers could lead to technical infeasibility or high grid upgrade costs. Implementation of market mechanisms and regulations supporting prosumers can enable the greater inclusion of EVs. Charging EVs from rooftop solar PV systems prove to be most beneficial and regulatory frameworks should promote smart chargers, encourage optimal PV-BESS sizing, and define clear grid connection standards. Targeted infrastructure upgrades, prioritising feeders with low hosting capacity but high EV adoption potential, should also be considered (IRENA, 2025 unpublished).

The European Network of Transmission System Operators for Electricity (ENSTO-E) network codes assume that EVs fall within the scope of codes for generation units (IRENA, 2022). An EV in the unidirectional controlled charging mode would fall within the ENTSO-E Demand Connection Code and vehicle-to-gird would fall within its Requirements for Generators.

Figure 13 Forms of smart charging



Source: (IRENA, 2019d).

5.3.3 Demand-side management strategies

DSM refers to a portfolio of measures to reduce energy consumption and/or adapt it according to the conditions and needs of the power system (*i.e.* make the consumption flexible/demand side flexibility). DSM measures range from energy efficiency improvements, to use time-dependent tariffs intended to modify consumption patterns, to real-time control of loads (*e.g.* demand response to market signals or operator requests). In Palensky and Dietrich (2011), DSM is categorised into energy efficiency measures, time-of-use tariffs, market requested and operator-requested demand response, and spinning reserve, where spinning reserve refers to a fully automatic demand response. Within the context of SIDS, DSM measures have the potential to maximise the benefits of renewable energy, improving economic stability and promoting energy independence. Improved situational awareness achieved by improved system monitoring and automation can significantly enhance the flexibility and reliability of the system.

In Dietrich *et al*. (2012), the impact of DSM on the economic operation of the Spanish island of Gran Canaria, with high wind generation, is presented and shows how DSM is crucial to reduce curtailment of wind power. In (Liu *et al*., 2018), initiatives including the implementation of DSM were assessed for five prototype islands, representing nearly 60 island power systems. DSM seems to be an attractive alternative for larger islands. By implementing advanced demand response programmes, SIDS can shape their energy consumption patterns to align with the availability of renewable generation, reducing the need for fossil fuel-based backup power.

Intelligent controllers and communication networks can provide the option of automated demand response from appliances, industrial networks and other flexible loads. This automated response will ensure that dynamic shifting of energy is possible from peak periods to periods where high VRE generation is available. Additionally, grid stability and resilience can be improved through demand response. Policies that ensure and incentivise the adoption of demand response should be implemented.

5.4 Emerging stability markets: overview and opportunities

Ancillary services refer to those services needed to guarantee reliable system operation. Ancillary services can be broadly grouped into frequency and non-frequency ancillary services, procured from active power and reactive power reserves. The system operator or network operator procures these services from system users. In the past, ancillary services, such as primary frequency reserve and voltage control, have been mainly provided by conventional synchronous generation. The increasing penetration of VRE, together with the modifications in grid codes, have enabled VRE generation to provide certain ancillary services. The grid codes define and enforce the ability to provide ancillary services, but the offering and actual assignment of these services depends on the market design.

An intrinsic feature of synchronous generation is its ability to provide immediate responses to changes or disruptions in the system. The crucial role of this attribute in guaranteeing the stability of the power system, especially during fault situations, is not explicitly acknowledged in most grid regulations and ancillary market designs. Historically, synchronous generators operating in the wholesale market have naturally offered stability.

The increasing penetration of VRE has led to a reduction in available inertia, but a minimum amount of inertia can be guaranteed by redispatching synchronous generation. Another solution is defining new ancillary services, such as fast frequency response (FFR), consisting of rapidly injecting additional active power when frequency falls below a certain threshold. As discussed in previous section demand-side flexibility and the deployment of DERs creates new opportunities among SIDS stakeholders to participate in the ancillary services market. Incentivising and rewarding assets for the provision of grid-supporting functionalities through a competitive bidding process is possible when markets have clear definitions for actively managing loads, providing reserves, offering rapid response capabilities and identifying new streams of income.

The benefits extend beyond direct revenue. Participating in grid services markets incentivises investment in the technologies that enable flexibility, leading to a more resilient and adaptable power system. During grid disturbances or outages, the ability to quickly adjust consumption or dispatch energy from distributed resources becomes invaluable for SIDS.

To address probable stability issues in the short term, some countries procure short-term stability needs through balancing mechanisms and trades within the operational time frame. The Stability Pathfinder initiative by the UK National Energy System Operator aims to identify and deploy the most cost-effective solutions to address stability issues in the long term. Under the initiative, stability service providers submit their solutions, which are then assessed by means of a feasibility study to ensure they meet the technical specifications. Tenders of feasible solutions are then assessed and compared to one another. The most cost-effective solutions, including the option of using the current balancing mechanism, are then selected to meet predefined stability requirements (*e.g.* overall inertia) (NationalGrid ESO, 2021). The National Energy System Operator's Stability Market Design innovation project aims to design a market for the procurement of stability services. A combination of a dedicated short-term market (day ahead) with a long-term market (building on the well-functioning pathfinder approach) for stability services, while retaining the balancing mechanisms as a backup, has been recommended (NationalGridESO, 2022). Units contracted and operational under the programme were zero-carbon synchronous compensators and deliver inertia into the network. Although long-term markets are appropriate for securing significant new capital expenditure-heavy investment, they suffer from the long-term unpredictability of system needs and cannot accommodate service providers that are unable to make long-term commitments due to uncertain availability, unpredictable costs, and so on. Adding a short-term market would offer a route for providers that are not able to make long-term commitments and is expected to reduce the need for actions in the balancing mechanism, which brings benefits in terms of dispatch efficiency and carbon reduction. The grid code specification for grid-forming capability would form the basis of a future short-term stability market. It would give certainty to developers of the requirements they would need to meet in a transparent way.

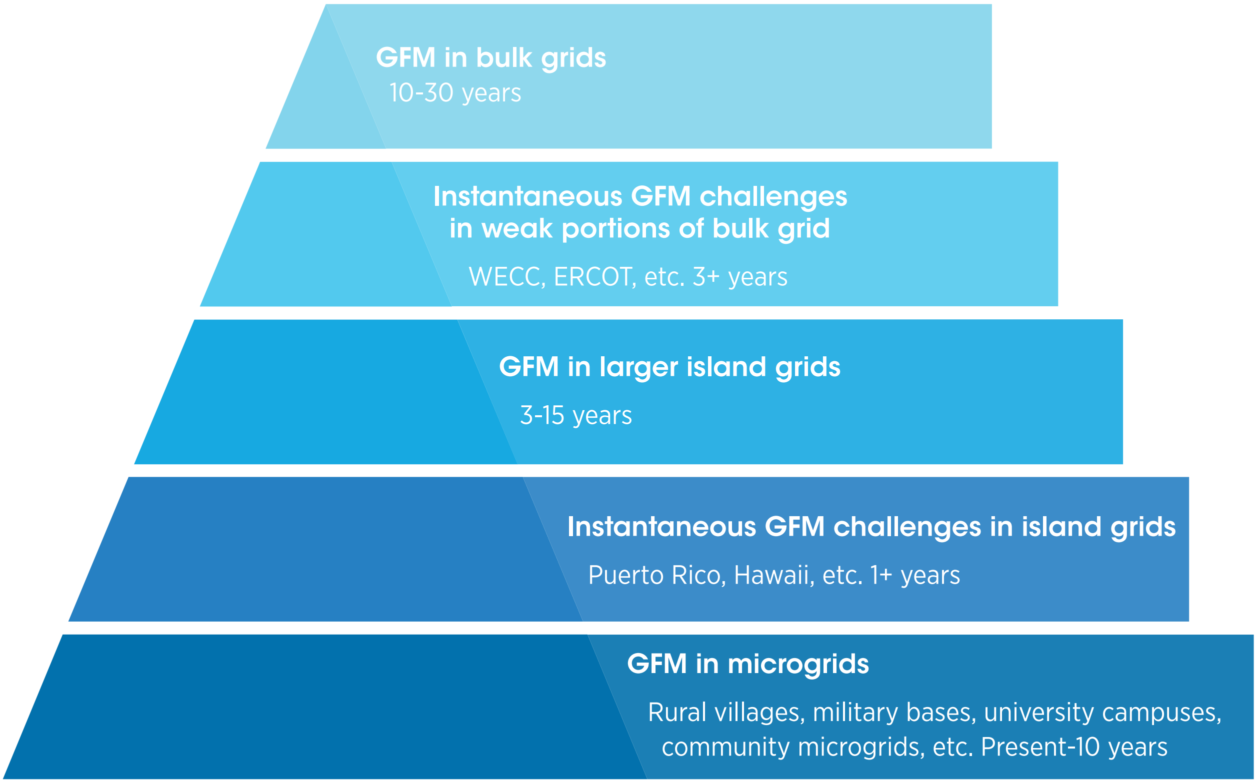
5.5 Grid-forming inverters enabling ancillary service participation in SIDS

The increasing penetration of VRE leads to the substitution of conventional synchronous generation in the generation mix. Inertia and short circuit currents are mainly provided by synchronous generation which then reduces. Grid-supporting functions traditionally provided by synchronous generation should therefore be replaced by alternative means.

One alternative is to modify the control scheme of the inverter-based (non-synchronous) elements (VRE generation, BESS, etc.). Currently, grid-side inverters of VRE generation are operated and controlled in grid-following mode. This operation mode ensures the injection of active and reactive powers (*e.g.* the maximum wind power available, determined by the maximum power point tracking), and for this purpose, the inverter and its controls need to be synchronised with the grid, which in turn requires a sufficiently strong grid and a phase-locked loop.

By contrast, if grid-side inverters were operated and controlled in grid-forming mode (GFM), they would impose a voltage and a frequency to the grid according to the active and reactive powers required by the grid and measured by the inverter. Voltage and frequency could be adjusted by means of droop control, virtual synchronous machine controls, oscillators, matching controls, and so on. This resembles the working principle of a synchronous generator, where the rotational speed (frequency) changes after a request of active power by the grid due to a disturbance and is corrected by the speed governor system acting on the turbine, releasing reserved power. Grid-forming capability therefore requires not only a suitable control scheme but also sufficient power and energy margins. This is similar to microgrids, where at least one element functions in grid-forming mode.

Figure 14 Incorporating grid-forming controls into the electric grid – a gradual approach



Source: (Lin et al., 2020).

Notes: GFM=Grid forming mode; WECC= Western Electricity Coordinating Council; ERCOT= Electric Reliability Council of Texas.

Currently, power system restoration follows a top-down approach, by gradually starting up large generators connected to the transmission system and synchronising load. To black start a generator, it must have black-start capability, which requires an independent source to supply auxiliary loads of generators. Almost all VRE sources are currently based on grid-following inverters, which cannot impose a voltage and a frequency, and such VRE sources do not include an independent source to supply their auxiliary loads. The ability to operate in grid-forming mode is one of the prerequisites for having black-start capability. The VRE generator or BESS needs an independent and sufficient power and energy source to feed the auxiliary loads of the installation.

As of now, the application of grid-forming inverters is limited to pilot projects and standalone microgrids, and fully integrating these inverters will take place gradually after key functionalities have been demonstrated and confidence has been gained by operating them in smaller microgrids and island power systems. Although it has been shown that a 69 MW wind farm can black start and re-energise part of the grid, VRE sources can act as secondary resources supporting system restoration after an already successful re-energisation of the grid.

In the United Kingdom, the grid code has been modified by including the minimum specification required for the provision of grid-forming capability. The requirements are, however, not mandatory yet and are technology agnostic; that is, the grid-forming capability specifications do not only apply for converter-interfaced elements but also for synchronous machine-derived solutions (*e.g.* synchronous condenser) (Ofgem, 2022). Figure 14 highlights the phase-wise implementation of grid-forming inverters transitioning from microgrid to bulk grid (Lin *et al*., 2020).

6 Achieving grid stability with high renewable integration: Lessons and best practices

As discussed throughout this publication, SIDS face unique challenges in the energy transition but still emerge as leaders in renewable integration. There are several examples of SIDS harnessing the agility of their systems and using advanced technologies to integrate renewable generation sources to decarbonise the power system, even attaining 100% renewable generation at times. This indicates that grids heavily reliant on solar PV and wind generation can also operate securely and reliably with the right technology enablers. Some SIDS have also set targets to achieve 100% renewable energy generation. These actions speak to the commitment of SIDS to chart their own sustainable future. Although technology advancements are probable, grid codes and regulatory frameworks are other key enablers to grid modernisation and the uptake of renewables.

The establishment of performance-based incentives for grid operators, DER providers, and consumers unlocks a new era of responsiveness to the needs of the evolving grid. Incentives tied to grid stability, reliability metrics, and the integration of clean energy sources motivate stakeholders to actively contribute towards a more resilient, modern and sustainable power system. This marks a shift from mere compliance to a system driven by innovation and tangible, measurable outcomes that directly benefit SIDS. Regulatory frameworks for SIDS must transcend the role of constraint, transforming into powerful catalysts for technological and economic advancement.

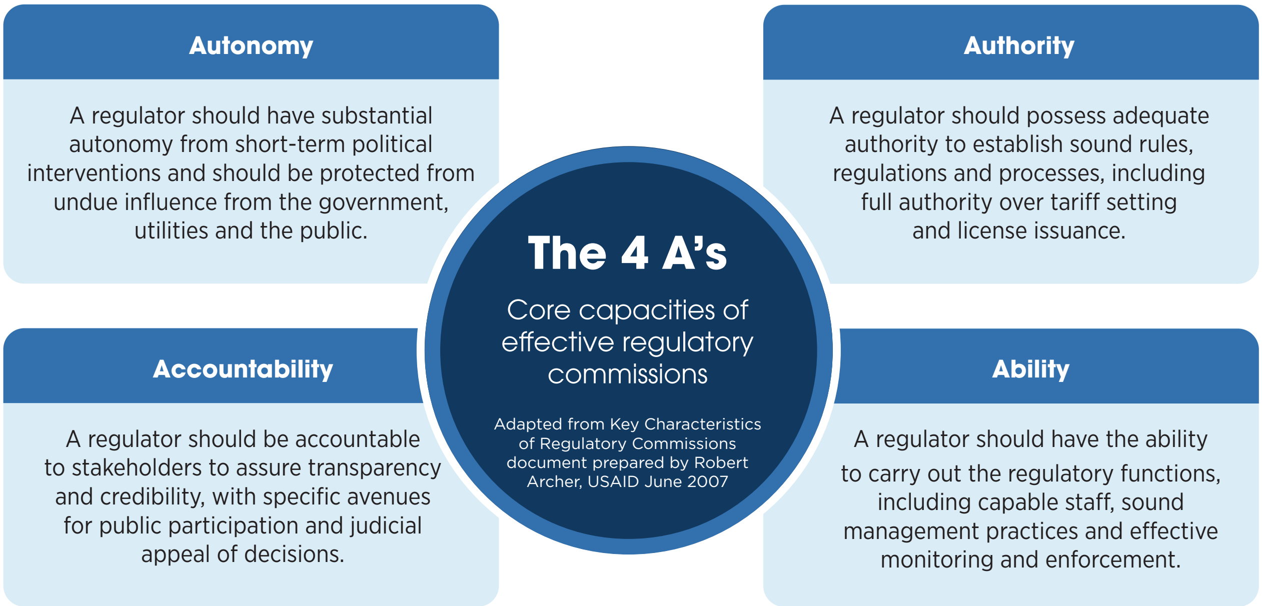
6.1 Regulatory frameworks and role of regulators

Regulatory frameworks need to evolve with time and with new technologies so as not to impede grid modernisation. To unlock the full potential of grid modernisation efforts, proactive regulatory reform is paramount. Creating an independent energy regulator with adequate capacities and competencies will provide significant impact. While the establishment of such a regulator still seems to be a pending issue in many cases, it could further enable the appropriate framework conditions to achieve the targets established. Regulators can provide support in overcoming resistance and in establishing enabling frameworks that promote the integration of renewables and grid modernisation. A well-defined regulatory framework also creates an investor-friendly ecosystem, inviting the resources needed to deploy renewables and modernisation technologies.

Regulations, including system operation regulations and guidelines such as grid codes, coupled with performance-based incentives and the right market regulation and mechanisms, will lay the foundation for an agile and supportive regulatory environment tailored to the unique needs of SIDS. The presence of regional regulatory agencies such as the Office of the Pacific Energy Regulators Alliance could be helpful in promoting knowledge sharing among regulators.

Figure 15 highlights autonomy, authority, accountability and ability as the "4A's" that can enable regulators to set up a well-functioning energy sector (USAID, 2019).

Figure 15 Essential principles for regulators



Source: (USAID, 2019).

Key strategies include:

- **Framing grid modernisation as an opportunity:** It is key that the need for energy independence and the resulting economic opportunities are highlighted. Therefore, grid modernisation could be showcased as an opportunity for achieving sustainable energy targets.
- **Pilot projects:** To understand the benefits from grid modernisation, it crucial to see the results upfront, and this will be possible through pilot projects. This will enable stakeholders to make informed decisions on the uptake of technologies, paving the way for large-scale deployment.
- **Collaboration and shared ownership:** Engaging with local communities in the very beginning of the project phase will help garner more support to ensure that efforts towards sustainability are taken forward. The involvement of all stakeholders can support the implementation of these efforts and ensure that the benefits from them are equitably distributed.
- **Economic advantages of grid modernisation:** Highlighting the contribution of grid modernisation to employment opportunities and skill development, leading to the development of local capacities, industries and affordable energy, can create a favourable environment among policy makers for the uptake of these technologies.
- **Knowledge sharing through collaborations:** International collaborations through partnerships and knowledge-sharing platforms can provide peer-to-peer learning opportunities. This will offer important insights from case studies across the world to bring about regulatory transformation.
- **Innovation in regulations:** The size of the power systems in SIDS make them ideal for new innovations in regulations, without there being too many risks. This characteristic could support the uptake of technologies that can offer greater benefits to the system and the community. This could be achieved through effective and transparent communication with the different stakeholders.

Regulatory frameworks should evolve alongside technological advancements, proactively addressing issues like the network connection and system operation requirements, the integration of DERs, grid-forming DERs and the participation of consumers in ancillary service markets.

6.1.1 Tailoring operational guidelines for SIDS

As discussed, grid codes need to evolve to foster the seamless integration of DERs and variable energy sources. They should be conducive to the inclusion of new technological enablers, such as advanced inverter configurations and energy storage; allow DERs to provide ancillary services; and facilitate participation in energy markets. Proactive engagement with incumbent utilities (where applicable) is essential to ensure that these reforms align with the specifications of existing infrastructure.

Figure 16 highlights examples of some of the technical requirements from VRE.

Figure 16 Technical requirements from variable renewable energy - Wind power plants

Power quality

- The total harmonic distortion of current should be ≤ 5% of the rated fundamental frequency
- The maximum harmonic distortion levels at the PCC shall comply with IEEE 519-1992 standards

Voltage control

- China: WPPs should be equipped with reactive power regulation and voltage control capacity
- ERCOT-US: WPPs are required to provide sufficient dynamic voltage support

Active power feed-in at over-/ under- frequency

- The active power of a WPP shall be reduced according to the power system dispatch centre
- Frequency response from WTGs is required for low frequency and only when WPPs are curtailed/or in deloaded condition

Voltage ride-through capability

- When the voltage at the POI drops to 20% of the nominal voltage, the wind turbines shall not disconnect for 625 ms
- If the system voltage is higher than 15% of the nominal voltage for a period that does not exceed 0.625 s, the WPP must stay online

Advanced forecasting

- China: Stipulated forecasting for WPPs capable of providing 0- to 2-hour and 15-minute to 4-hour wind power forecasts

Automatic generation control

- United States: Utilities can request all WPPs to install AGC equipment
- Incentivising VRE participation in frequency regulation is considered

Source: (IRENA, 2022).

Notes: AGC = automatic generation control; IEEE = Institute of Electrical and Electronics Engineers; ms = milliseconds; PCC = point of common coupling; POI = point of interconnection; VRE = variable renewable energy; WPP = wind power plant; WTG = wind turbine generator.

Most IRENA studies recommend implementing FRT capability in VRE generation in order to withstand fall in voltage (IRENA, 2013, 2015c, 2016a). For instance, the study for Viti Levu suggested adapting the Fijian grid code to one with similar specificities with respect to FRT and low-frequency ride-through, such as the Australian grid code, but accounting for the system specificities of Viti Levu (IRENA, 2018a). It is also advisable to enable dynamic voltage support from VRE during faults (IRENA, 2013). According to the studies conducted in Antigua, Aitutaki, Dominican Republic and Upolu, it is recommended that VRE not only offers voltage control in steady state but also provides voltage support during faults. This means that VRE should be capable of injecting reactive power currents as part of fault response. Overall, evaluations clearly indicate that VRE should offer a range of grid-supporting functions. These functions include voltage controls and the injection of reactive power during faults. Additionally, they should help reduce active power in the event of over-frequency (IRENA, 2015c, 2015b, 2018a) and contribute to power frequency control capabilities in general (IRENA, 2015b, 2020).

Renewable energy systems that provide power frequency control in both upward and downward directions must allocate a power margin for upward reserve. In the case of wind and solar PV generation, this could be accomplished by operational deloading. VRE penetration is growing not only in bulk power systems but also in distribution systems, affecting smaller users. The grid codes have traditionally concentrated on major conventional users linked to the bulk power system, such as generators and demand. However, they are now expanding to include smaller-scale users and new user categories. The European grid regulations, for example, categorise generator types based on their size and connection voltage level into four different types. Of relevance here are generators designated as Type A and Type B, connected at voltages below 110 kV and in sizes above 0.8 MW and between 1 MW and 50 MW, respectively. These generators are intended for users with low-voltage and medium-voltage connections. The regulations governing Type A generators should guarantee that there is no significant decrease in power production throughout the operational ranges of the system, thus reducing the occurrence of critical events. These regulations should also include the provisions necessary for widespread intervention during system-critical (IRENA, 2022).

Controllability requirements for distributed VRE

Controllability requirements are increasingly being extended to distributed VRE generation, such as rooftop solar PV (IRENA, 2022). Grid codes provide requirements for automatic local controls as well as for following system operator instructions. Type A generators need to be able to reduce power output during frequency increase and need to be equipped with logic input ports to cease production within 5 seconds (s). Type B generators have wider requirements and, for instance, must be able to reduce production upon request, recover post-fault active power once voltage levels have reached certain thresholds, and reconnect after a fault. Following system operator instructions requires communication interfaces and control system integration. IEEE 1547-2018 provides for three communication protocols, although others can be used under agreement.

Low-voltage ride-through requirements have usually been specified for generators connected to medium-voltage and higher-voltage grids. Typically, the requirement applies at the high-voltage terminal of the generator transformer. Now, these requirements are being extended to grid users at low voltage as well. Unlike at higher voltage levels, low-voltage ride-through envelopes for low voltage do not extend down to zero residual voltage. Some grid codes, like the German grid code, state that non-synchronous generation does not have to withstand residual voltages below 15% of the nominal voltage (IRENA, 2022). However, IEEE 1547-2018 does not consider the voltage level of the connection point in the specification of its low-voltage ride-through requirement.

Evolving grid codes for energy storage and DSM

With the introduction of BESS and generation behind the meter, the distinction between power-generating and power-consuming grid users is becoming variable in time and less clear. The European Union grid codes do not include specific requirements for energy storage but stipulate that such storage should meet the same requirements as a generation unit.

One key operational measure that SIDS can adopt to support the inclusion of DERs and VRE is adopting grid codes that address the inclusion of demand-side flexibility measures and those that address how consumers can manage their consumption so as not to load the grid at critical moments. Supported by smart meters, grid codes can enable DSM from storage systems using a framework for remuneration, such as dynamic pricing or compensation for services from batteries and EVs, in the provision of demand-side flexibility.

Box 4 Examples of inter-island grid code harmonisation

The island nations of Indonesia and Philippines, both comprise of hundreds of different islands, and of different sizes. In the case of Indonesia, more than 600 different power systems are operated by national utility PLN, while Philippine grids are operated by separate distribution companies. Connection requirements and operational strategies differ greatly from one island to the other, making widespread integration of VRE difficult. Efforts are being undertaken in both countries to harmonise nationally applicable rules.

The Philippines published its Small Grid Guidelines in 2013, but they mainly contained requirements for grid operators and conventional generators and addressed VRE deployment in 2018. Though no harmonised guidelines have been published to date, the structure that addresses the commonalities and differences between individual small grids can be used as a template.

In Indonesia, the grids are theoretically subject to the applicable national distribution code and an additional Renewable Energy Connection Guideline, but neither document addresses the additional functionalities required for generators. The obvious benefits that could be obtained from VRE generation and greater interest from IPPs, have pointed out the need for harmonised rules. National utility PLN is currently revising its distribution code, and a small grids section addressing special requirements for VRE in island systems has been developed. This outlines the technical and operational MV and HV compliance requirements for intermittent resources like wind and solar PV.

6.1.2 Grid code adaptations in islands

Case study 1: Regulatory frameworks for VRE integration in Spanish island grids

The Spanish isolated power systems include the power systems of the Canary Islands, the Balearic Islands and the two autonomous cities of Ceuta and Melilla. The Canary Islands have six power systems, the two autonomous cities have two power systems, and the Balearic Islands also have two power systems, although Mallorca is connected to the Iberian Peninsula through a high-voltage DC link.

Table 6 outlines relevant features of the systems of the Spanish Canary Islands, where renewable generation mainly consists of solar PV and wind generation – although on El Hierro a relatively large pump storage power plant exists, and another one is under construction on Gran Canaria. VRE generation on the Canary Islands amounted to about 20% of the total electricity generation in 2021, whereas monthly and daily renewable energy generation can exceed 30% and 45% of the total electricity generation, respectively (Red Electrica, 2023).

Table 6 Features of the systems of Spanish Canary Islands

System	Electricity generation (GWh)	Installed capacity (MW)	Peak demand (MW)
Tenerife	3 625	1 084.28	593
Gran Canaria	3 653	1 111.8	598
Lanzarote-Fuerte ventura	1 458.7	377.97	256.5
La Palma	254.8	105.52	48.4
La Gomera	66.7	20.1	12.1
El Hierro	35.7	11.31	7

Source: (EU, 2023).

Notes: GWh = gigawatts hour; MW = megawatts.

The economic regulation of the Spanish isolated power systems stipulates electricity generation from pumped storage power plants to improve security of supply and the techno-economic operation (Ministerio de Industria, Energía y Turismo, 2023). The regulation states that a minimum amount of dispatchable generation needs to be considered that guarantees the provision of sufficient inertia and spinning reserve. In this sense, the penetration of renewable generation is maximised up to the limits imposed by security of supply. Although the feasibility of installing different ESS has been shown for some of the Canary Islands (Egido Cortés *et al.*, 2016), the economic regulation only considers pump storage power plants; other ESS have not been contemplated so far.

Technical operation is regulated by a set of operational procedures, including network connection and system operation grid codes. Network connection requirements have been aligned with the European network connection grid code and apply to all generating units connected to the transmission network or those generating units connected to the same distribution network bus, with an accumulated capacity larger than 1 MW.

While the Spanish mainland power system requires normal frequency fluctuations to be within ± 50 millihertz (mHz), the normal frequency fluctuations on the island are expanded to ± 150 mHz. The dispatch determines the allocation of reserves for the isolated power systems, while a minimum primary reserve of 1.5% of the nominal capacity is mandated for each generating unit in the mainland. The spinning reserve is designed to mitigate the impact of the largest load-following event, such as an outage of the largest online unit, or a probable reduction in renewable generation.

Case study 2: System services for high VRE penetration: the Irish approach

The peak power demand of the all-island power system that includes Ireland and Northern Ireland is approximately 6.9 gigawatts (GW). The annual demand for this system in 2021 was 38.6 terawatt hours. Renewable energy generation mostly comprises wind generation, with a relatively minor contribution from hydro, solar PV and other generation technologies. The existing installed wind-generating capacity is approximately 5 600 MW. Annual renewable energy production accounted for around 35% of the overall electricity production in 2021, while monthly wind generation could surpass 50% of the total electricity production (EirGrid, 2022).

There is a grid code for the bulk system, and a separate distribution code exists for distribution systems (IRENA, 2022). The grid code is structured into a planning code, a connection code, an operation code, a scheduling and dispatch code, and a controllable power park module code. The latter includes specific requirements for non-synchronous generation. A multi-year initiative, Delivering a Secure, Sustainable Electricity System (DS3), was initiated by EirGrid Group in 2014. The objective of the DS3 initiative was to achieve Ireland's 2020 electricity goals by progressively augmenting the integration of renewable energy sources into the Irish power grid in a manner that ensures safety and security. Three primary pillars underpin the DS3 programme: system performance, system policies and system tools (EirGrid *et al.*, 2014). This was then replaced by the Future Arrangements for System Services programme, which aims at achieving even higher levels of system non-synchronous penetration SNSP. The goal is to achieve renewable energy penetration of 80% and SNSP of 95% by 2030 (EirGrid and SONI, 2018).

There are 14 system services, categorised into five main groups: reactive power or voltage control, inertial response, fast-acting response, reserve, and ramping. Synchronous inertial response (SIR),[2] Fast frequency response (FFR) , ramping and post-fault recovery services are included in this. SIR and FFR are mainly related to the expected and observed decrease in system inertia, whereas ramping is related to the variability of renewable generation. FFR is a rapid injection of active power in response to changes in frequency. FFR is triggered when the frequency drops below a specified threshold, and the power to be injected grows in a linear manner with relation to the frequency. FFR can be supplied by units of generation, storage and demand. FFR needs to be delivered in at least 8 s.

The SIR factor, being inversely proportional to the minimum stable generation, must be higher than 15 s to be eligible for payment. The continuous monitoring of the system in relation to the largest possible contingency has allowed the adaptation and reduction of the inertia floor[3] to 23 GWs. The more frequent system monitoring has enabled stability analysis with real-time data and short-term forecasting, further increasing instantaneous renewables, particularly VRE penetration. Finally, the requirement regarding the ability to withstand RoCoF has been increased from 0.5 to 1 Hz/s, measured over a 500 millisecond (ms) sliding window. Wind farms with a capacity exceeding 5 MW must possess the capability to react to fluctuations in the active power set point and manage frequency response and voltage control.

2 SIR is the kinetic energy of a centrally dispatched synchronous unit multiplied by the SIR factor. The SIR factor is the ratio of the kinetic energy (at nominal frequency) to the lowest sustainable megawatt output the unit can operate at while providing reactive power control (Eirgrid, 2022).

3 The inertia floor is the minimum level of kinetic energy stored in rotating plants operating on the system. Inertia comes from synchronous generation, motor load and transmission assets (synchronous condensers) (Eirgrid, 2022).

Case study 3: Operational strategies for VRE in Philippine island grids

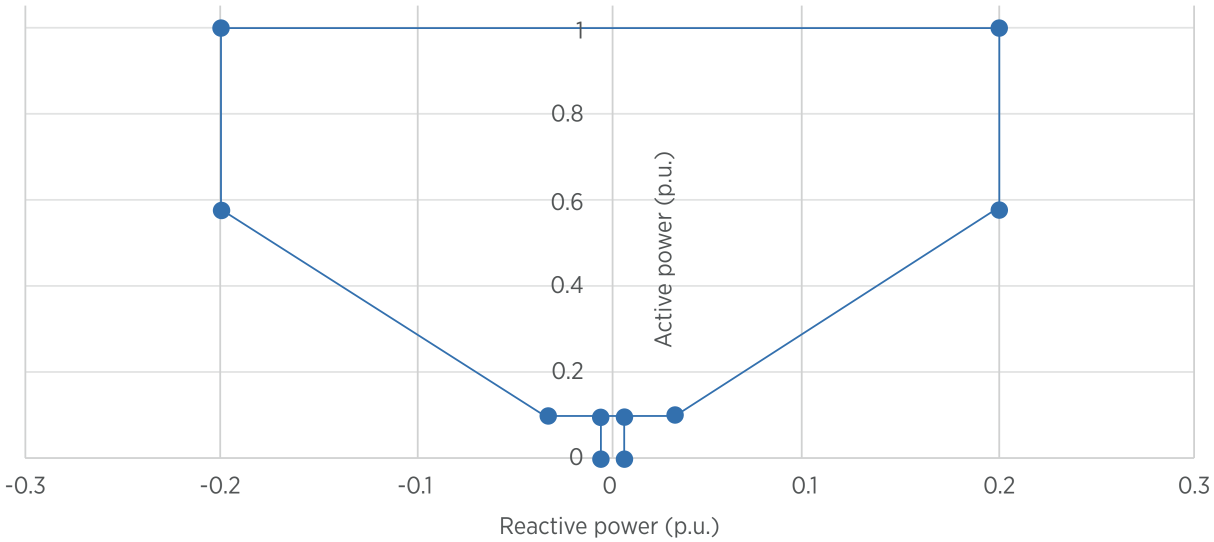
The Philippines consists of over 7100 islands in the Pacific Ocean. There are three large asynchronous power systems (Luzon, Visayas and Mindanao) operated by National Grid Corporation of the Philippines. The Philippines' generated 21% of its electricity from low carbon sources in 2024, 8% from hydro-power and 3.8% from Solar and wind. It aims to have 35% renewable electricity by 2030. Smaller power systems are operated by separate distribution utilities (Ember, 2025).

The grid code governs the various users of the Philippine transmission system with a distribution code covering the lower voltage levels. Whereas the first versions of the grid code mainly focused on synchronous generation, the 2016 edition was developed to, among other objectives, to adopt and fully implement the connection and operational requirements for VRE consistent with the Republic Act No. 9513 (Renewable Energy Act of 2008) (Energy Regulatory Commission, 2016b).

The grid code specifically differentiates between large and non-large (small) generation units. This reference to the size of the generation plant is system dependent: 20 MW for the Luzon power system and 5 MW for the Visayas and Mindanao power systems. For smaller generation plants, power quality, voltage and frequency variation withstand capabilities are required; connection requirements for larger generation additionally refer to the monitoring and control capabilities. Large wind and solar PV generation plants need to be connected to the systemwide SCADA; they must provide reactive power support during faults, and they must be able to operate under different active power control modes (free, active power limitation and active power gradient limitation). The static reactive power requirement for wind farms is shown in Figure 17. The grid code recommends no absorption of reactive power by a wind farm during fault and during fault recovery, but the wind farm should inject the maximum possible current. During under-frequency conditions, these plants should operate in free mode (no limitations); during over-frequency conditions, they should reduce the generation by means of a proportional law (droop control).

The 2016 edition of the Philippine Grid Code also includes operational requirements for the system's frequency response, where the system's frequency response characteristic is determined by the overall governor droop (*i.e.* the generator's primary frequency control) and the load-damping effect. The frequency response obligation imposes a minimum system frequency response characteristic. The frequency response obligation is determined according to a critical contingency and such that the resulting steady-state frequency deviations are within limits (*e.g.* for the Luzon power system, the minimum frequency response characteristic amounts to 750 MW/Hz).

Figure 17 Reactive power requirement: wind farms in the Philippine Grid Code



Source: (Energy Regulatory Commission, 2016b).

Note: p.u. = per unit.

With respect to the overall primary frequency control, the grid code stipulates that primary frequency control can be provided not only by synchronous generation but also by other elements, such as BESS and flywheels. The ability to provide primary frequency control needs to be certified. If frequency deviations exceed imposed thresholds or if reserve becomes exhausted, the system operator should make use of must-run units or redispatch generation to ensure security.

Lastly, the Philippine Grid Code mandates that the system operator generate and submit an aggregated VRE forecast to the market operator. The grid code also includes requirements for the periodicity of forecast updates, forecast periods, forecast horizons, and error. The system operator should therefore receive forecasts from VRE generators that include specified minimum performance indicators.

The Small Grid Guidelines, released by the Energy Regulatory Commission of the Philippines specifically addressed smaller power systems that are managed by independent distribution companies. The Small Grid Guidelines establish a benchmark for small grid operations, to guarantee secure and efficient operation, prescribe equitable and unbiased connection regulations, and define operating states and criteria. The guidelines classify small grids into five categories. The distribution utility is responsible for conducting day-ahead load forecasting and dispatch scheduling. This is done based on the fundamental requirement that the synchronised generating capacity must always be enough to meet both the projected demand and the necessary 2.8% load following. The guidelines states that the system operator should prioritise dispatching renewables without compromising operational reliability and that the distribution utility must conduct a system impact study to guarantee security.

Case study 4: Grid code formulation in Seychelles

Electricity demand in Seychelles has increased significantly since 2010 (UNECA, 2021). The Public Utilities Corporation provides electricity to the three major islands: Mahé, Praslin and La Digue. La Digue and Praslin are interconnected through a submarine cable.

The Seychelles Energy Policy 2010-2030 sets a goal of 30% of electricity generation coming from renewables by 2030. Promotional and incentive schemes, including tax exemptions or low-interest loans, have been introduced to boost the penetration of renewables. Until 2012, the Public Utilities Corporation was the sole generation provider, but the Energy Act 2012 has opened the generation sector to private participants to promote generation from renewables. Subsequently, the connection of small-scale solar PV systems (below 100 kW) has been carried out according to the Public Utilities Corporation's internal standards and on an *ad hoc* basis, whereas the connection of independent power producers above 100 kW has been done on case-by-case basis (DNV GL, 2018). This led to consistency problems, giving rise to the development of a grid code in 2018.

The grid code is structured into a planning code, a connection code and an operation code. The grid code takes British Standards as a reference and very much resembles in its structure the grid code of the Irish power system. The grid code explicitly differentiates between controllable and dispatchable renewables, where the latter is a renewable generation with a dispatch centre (control facility) subject to central dispatch if above 200 kW. In the planning code, information on variability from VRE is required for VRE generation. Dynamic models of renewable generators and their validation are also required. The grid code explicitly mentions storage devices with respect to dynamic model requirements.

In addition to frequency ride-through, FRT requirements, and similar, generators are also needed to provide primary and secondary reserve; the amount of reserve to be provided is dependent on the renewable penetration level. The operating code states that dispatchable renewables above 200 kW have to provide ancillary services. Primary frequency control is delivered by, among other things, the automatic megawatt output adjustment of dispatchable renewables, by wind or solar PV generators if combined with BESS, and automatic load adjustment via demand-side aggregators. The performance of primary frequency control provision needs to be monitored. Dispatchable renewables above 200 kW should also have automatic generation control, and provide voltage control by maintaining a constant terminal voltage. The operation code also specifies the operating margin, which consists of primary, secondary and tertiary operation reserves. The amount of the operating margin depends on the largest generation infeed, the predicted frequency drops due to the loss of the largest generation infeed, and the uncertainty of future VRE, among other factors.

The grid code does not provide any rules or regulations on dispatch, although references to a scheduling and dispatching are made. Economic merit order-based dispatch, market settlement rules, and regulation of curtailment seem not to be addressed.

6.2 Smart operational measures for grid stability

Critical operational measures for SIDS should centre on intelligent power system automation. Optimising dispatch and control systems allows for real-time balancing of generation and load. Further, a comprehensive re-evaluation of primary frequency control parameters and the UFLS scheme is vital to maintain stability in the face of VRE fluctuations. Proactive generation redispatch strategies must be developed, ensuring optimal system response and power quality even during unforeseen disturbances.

Given the growing penetration of VRE, it is crucial to have flexibility on both the supply and demand sides to guarantee adequate reserve capacity for quick response. While not optimal from a resource perspective, strategic VRE curtailment may be required at times to prioritise grid stability. Focused load-shedding operations will also be crucial in strengthening operational responses, enabling rapid grid balancing and maintaining system integrity. Although no one solution is universally effective, the efficient execution of these operational measures will establish a more robust and contemporary grid that can successfully support the sustainable energy goals of SIDS.

Adapting protection schemes

The response of a power system after a generation-load unbalance mainly depends on the size of the disturbance, the system's inertia, and the response speed of the primary frequency control. Generator droop settings should be reviewed and updated to improve primary frequency control.

The use and implementation of UFLS schemes is recommended. Most systems already use UFLS schemes, being a last-resort tool to protect the system by shedding load. To improve the efficiency of existing UFLS schemes, they should be updated and redesigned. In general, the settings of frequency and voltage protections, among others, should be adjusted to avoid accidental tripping.

Must run units for improved stability

Generation redispatch enables increased system inertia and enhances primary frequency control response by dispatching additional units, with additional reserve and primary frequency control capacity. In addition, generation redispatch can also be applied for overload mitigation and steady-state voltage control by redirecting power flows and adding further reactive power resources. If a problem is identified during the security assessment stage of standard operational planning, the generation schedule is adjusted to address the technical limitation.

Strategies for reserve optimisation to mitigate VRE variability

The economic dispatch (ED) decides the power from each generator to meet the demand at the lowest cost possible. To maintain reliability, ED also ensures the availability of enough spinning reserves. The economic dispatch typically considers the outage of the largest unit as a reserve calculation criterion, also known as N-1 criterion. In systems with a large amount of VRE generation in the distribution feeders, such feeders behave similar to a large generation unit and if this feeder trips, it is like the tripping of another big generation unit of larger capacity. Going by the traditional N-1 principle, if the feeder power export can be limited to the amount equal to the largest generation unit in the system, then the automatic spinning reserves can step in to maintain stability and reliability. This way, the size of a disturbance resulting in the loss of an exporting feeder is limited and thus is its impact on the system response. In other words, the impact of the potential loss of a distribution feeder with a large amount of embedded VRE is limited.

To increase reserve availability and reduce VRE curtailments, the minimum technical operational limit of conventional generators can be reduced. Reserve requirements and VRE spillage can be reduced by carrying out more frequent, intra-hour dispatches or, in the case of market-based operations, by adopting intra-day markets with more frequently updated VRE forecasts. Spinning reserve criteria must be regularly reviewed and updated to ensure grid reliability in systems with increasing VRE penetration. Outdated criteria, as seen in the Antigua power system study by IRENA, may lead to insufficient operating reserves, resulting in UFLS events as a means of emergency balancing. IRENA studies conducted in Upolu, Palau and Viti Levu also underscore the necessity of incorporating intra-hour VRE fluctuations into reserve calculations. This can be achieved by considering time windows that align with the start-up and synchronisation times of conventional generators (10-15 minutes).

Grid stability assessments and operational planning should also consider the characteristics of VRE, especially the ramp rates of renewable energy resources, which could help identify pre-emptive actions for sudden contingencies.

Mitigating VRE curtailment: a multi-stakeholder perspective

Curtailment of VRE is a paradoxical measure: At one end, the aim is to maximise use of VRE generation to decarbonise the power sector; at the other end is curtailment due to the limitations in the network. Table 7 highlights the different stakeholder perspectives on curtailment. Curtailment also arises from a mismatch between the VRE generation and demand and the lack of flexibility in the system. The inefficient allocation of resources due to the technical constraints of legacy systems and unfavourable market mechanisms, which can lead to curtailment, are a concern for policy makers who need to make decisions on implementing renewable projects. Policy makers need to be made aware of the need to bring in solutions that can reduce curtailment, such as storage and advanced forecasting, which can introduce more flexibility and enable demand response programmes. Consumers also bear the brunt of curtailment as they will continue to pay higher prices for energy, which defeats the very purpose for which renewables were introduced.

Table 7 Stakeholder perspectives on curtailment

Stakeholder	Perspectives on curtailment
Government	From the government perspective, curtailment indicates a loss of economic resources that could have been allocated elsewhere, in addition to the non-optimal use of VRE. This impedes energy independence and the achievement of decarbonisation targets. Policy interventions aiding grid modernisation and upgrades through regulatory frameworks and innovative financing to bring in advanced technologies are crucial.
Utilities	System stability is critical for the smaller-sized island power systems, and utilities may consider curtailment as an option when faced with constraints introduced by variable renewable energy. At times and specific to systems, curtailment may become necessary, but it is something that can be rectified through grid upgrades and power flow technologies, flexibility measures and enhanced forecasting.
Regulator	Regulators play the critical role of creating market structures that promote the deployment of VRE and the need to maintain grid stability. Curtailment is a signal of market inefficiency, and introducing market mechanisms for ancillary service provision and voltage and frequency regulation, as well as re-evaluating tariffs to reflect the cost of system balancing, is key.

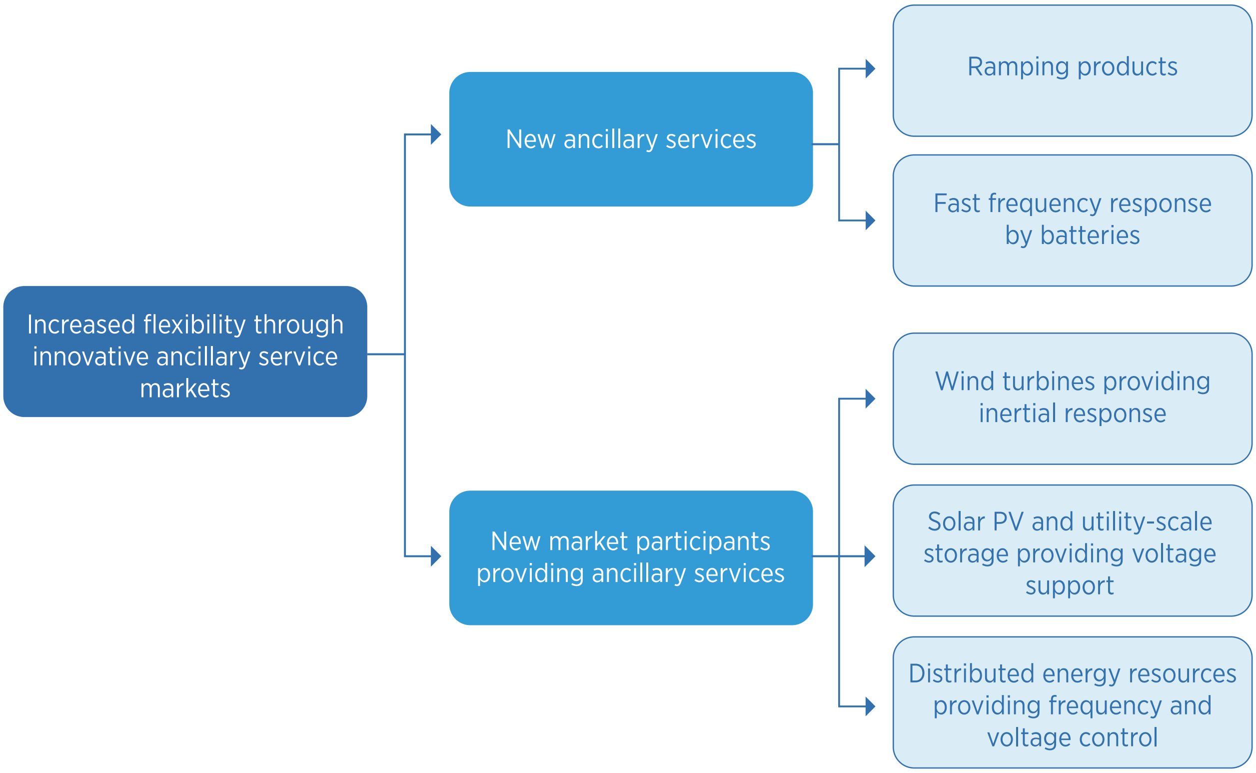
Customer	Consumers bear the economic consequences of curtailment through higher energy prices and continued use of fossil fuels. Systemic solutions should be put in place to ensure that prices are stable and that reliable and carbon-free electricity reaches consumers.
Developer	Depending on the market structure, curtailment can lead to negative pricing, affecting the viability of the project. Frequent curtailment can signal a long-term economic risk to the investor. Policies such as curtailment caps could limit curtailment to acceptable thresholds. Diversifying revenue streams or participating in demand response or ancillary service provision can offset the impact of curtailment.

Curtailment needs to be handled in a strategic manner with solutions that are system specific. Grid assessment studies can prevent curtailment through an evaluation of grid constraints based on the size, location and interconnection points of the project. It could be the implementation of enablers such as storage and forecasting, coupled with grid upgrades and modernisation strategies accompanied by advanced monitoring and control solutions.

6. 3 Maximising DER value in SIDS: the role of markets

The SIDS model showcases how DERs can be a catalyst for a more robust and financially sustainable energy future, demonstrating their value far beyond mere kilowatt hours. By participating in energy markets, DERs can generate revenue streams during grid outages, selling excess power or providing essential backup services. Business models address the viability of increasing VRE penetration in power systems, which is related to the benefits VRE can achieve to cover its capital and operational expenditures. Whereas large-scale VRE generation already participates in energy markets (where such markets exist) or is explicitly considered in the economic dispatch of island power systems, small-scale (mainly distributed) VRE generation on its own cannot participate in the markets and is not contemplated in the dispatch directly. This is due to lack of appropriate remuneration mechanisms. Furthermore, market participation requires operational control capabilities in the renewable generators and compliance with some minimum requirements, for instance on size. Figure 18 showcases the increased flexibility that can be achieved through ancillary services. Participation in ancillary service provision requires a technology enabler as well as a positive business case.

Figure 18 Innovations in ancillary services and examples



Source: (IRENA, 2019j).

For instance, in the Spanish island power system, small-scale VRE generation with a capacity below 1 MW does not need to have an associated control centre that communicates with the system operator. Aggregating small-scale renewable generation, for instance in the form of a VPP (Marinescu *et al*., 2022), can empower the participation of such generators in energy markets or make them visible to the system operator carrying out the UCED. Apart from participation in energy markets, VRE generation participates in ancillary service markets to achieve the associated benefits; its participation in frequency-related ancillary service markets is still marginal, although steadily increasing. The system operator of the Spanish island systems requires that generating units connected to the same distribution network bus with a cumulative capacity larger than 1 MW must be able to provide frequency-activated down reserves. The provision of frequency-related ancillary services, such as frequency control or inertia emulation (Morren *et al*., 2006), requires that deloaded operation of VRE generation is considered (*i.e*. operation below the maximum power point to have some headroom) or, in case of wind power generation, temporary overproduction can be contemplated (Liu *et al*., 2018).

The design of the energy and ancillary market can further foster the integration of higher shares of VRE. Although most island power systems operate under a centralised scheme (*i.e*. the system operator dispatches generating resources), the United Kingdom, for instance, is operated under a market-based scheme. In addition to increasing the time granularity from hourly to quarter-hourly settlement periods in the day-ahead market, the space granularity in markets can be increased. Increasing the locational granularity, for instance, by nodal prices captures the network constraints and conveys efficient locational signals. Finally, additional ancillary service products and markets (*e.g*. FFR, inertial response, and stability markets in general) are needed to cope with system needs and assign these needs efficiently among service providers.

7 Unlocking SIDS grid resilience: Enabling frameworks and investment strategies

Grid assessment studies can serve as an effective instrument for ensuring that SIDS integrate increasing quantities of VRE in a secure and efficient manner. To be truly beneficial, these studies must be system specific and properly aligned with both policy objectives and the short- and long-term decisions made by stakeholders, which are dictated by the regulatory framework in place. The scenarios and assumptions considered during the assessment must therefore be in accordance with the overarching policy objectives, as well as the investment and operational decisions made by all pertinent stakeholders during the implementation phase. The process must be streamlined and co-ordinated to achieve this. It is exceedingly impractical to evaluate scenarios that are at odds with the objectives of national policy. Similarly, an evaluation that is perfectly in accordance with national policy views is rendered useless if the investment decisions made by utilities or independent power producers are entirely independent of those views. This is why it is imperative to establish an enabling regulatory framework and engage stakeholders effectively. Doing so necessitates the development of several components, including the institutional framework, energy policy objectives, techno-economic analyses, and incentives and regulations that are intended to facilitate and mitigate obstacles to the efficient attainment of policy objectives. To ensure such particular characteristics are duly considered, the insights presented in this section are based on desk research – reviewing key reports and references addressing decarbonisation policies in SIDS – and a consultation among stakeholders from SIDS worldwide, comprising both an online survey and personal interviews with key actors. The objective of this section is to provide insights for policy makers and regulators on how to design enabling energy policies, and the associated regulatory frameworks, for efficient VRE integration in electricity grids.

7.1 Policy, institutional and legal foundations

Most SIDS have a strong political leadership that support the energy transition and have deployed appropriate institutional frameworks, including in most cases a dedicated agency or department in charge of energy planning. The vast majority of SIDS have energy policy targets in place. Most often included in these policy targets are renewable penetration, energy efficiency, greenhouse gas emissions, universal energy access, and electrification of end-use. Common drivers behind these targets are the need to reduce fossil fuel consumption and the cost of electricity and the need to enhance the security and the resilience of energy supply in the islands. Energy planning and roadmaps are also widespread, although these activities tend to be limited to the electricity sector, thus excluding other relevant sectors such as heating and cooling, cooking, or transport. In some SIDS, improvements could be made in both the assessment and siting of some new resources, such as geothermal. Lastly, land use planning and regulation is needed to ensure the sustainable development of renewables without affecting other land uses or land protection policies (50% of the SIDS reviewed have land availability constraints).

7.2 Incentives for hybrid renewable energy configurations in SIDS

Combining different technologies, such as wind, solar and energy storage, offers site-specific solutions and can maximise the strengths of individual assets, including operational efficiency and additional revenues. Implementing well-designed contracts for, and incentivising, hybrid projects with storage can also ensure systemwide benefits without curtailment.

The design of incentives for renewable energy deployment should also carefully consider the distinct technological and operational characteristics of different project configurations, including utility-scale renewable projects, behind-the-meter generation, and off-grid systems (including mini-grids and standalone installations). Effective support mechanisms must navigate a delicate balance between the following, sometimes conflicting, objectives:

- **Alignment with policy goals and cost-effectiveness:** Incentives should be structured to actively promote the installation of renewable generation that contributes to core energy policy objectives. Support schemes based solely on installed capacity (MW), without corresponding requirements for energy output or operational commitments, risk subsidising underperforming projects – the "money-for-nothing" scenario that policy makers must avoid.
- **Mitigation of risks and distribution of costs:** One of the key characteristics of incentives is the fine balance between risk mitigation and consumer interests. Robust risk-hedging strategies may be needed in SIDS due to the specific characteristics and risks that SIDS face and to ensure flow of capital.
- **Efficiency of operation and markets:** Market mechanisms that support the optimal and efficient operation of the system should be put in place. Incentives like fixed payments provided to incentivise renewable generation units can be counterproductive and lead to situations where the marginal cost of electricity production from the system is lower than the cost of the renewable generation, thereby justifying curtailment.

Feed-in tariffs (FITs) are the most well-known incentive provided to renewable generators and represent a fixed rate per megawatt-hour generated. Though FITs serve the purpose of de-risking renewable generation projects, they may not encourage efficient short-term operation. Integrating market signals into FIT schemes could help. As an example, suspending FIT payments when short-term marginal prices reach zero, or a negative value, can be beneficial.

Beyond simple directives for storage operation, key considerations towards hybrid configurations, that policy makers and regulators should address include:

- **Market participation:** Should the hybrid plant be treated as a single entity in energy and ancillary service markets, or should the renewable and storage components participate independently? The precise rules of participation and the contractual framework governing the hybrid plant's dispatch will influence its revenue streams and its responsiveness to system needs.
- **Incentive compatibility:** If the renewable component of the hybrid plant receives a FIT or another form of capacity-based support, how should storage operation be integrated into this scheme? Careful design avoids situations where the storage is incentivised to operate counter to the broader system interest to maximise the fixed energy payment.
- **Compensation mechanisms:** Diverse remuneration models can be considered for the storage component of hybrid projects. These models might include capacity payments that recognise the storage's ability to provide flexibility, performance-based payments linked to the provision of ancillary services (*e.g.* frequency regulation), or hybrid models that combine these elements.

- **Performance objectives:** The hybrid plant's performance metrics should be clearly defined in the contracts. These metrics encompass minimum state-of-charge requirements, ramp rates, response times, and expectations that govern charging and discharging behaviour to ensure that the system capitalises on the storage capabilities.
- **Operational flexibility:** Given the evolving nature of power system needs, contractual frameworks should retain a degree of flexibility to accommodate future changes in grid requirements or market structures. This adaptability protects both the investor and the system from being locked into rigid arrangements that lose their effectiveness over time.

The nuances of hybrid project contracts in SIDS warrant careful study. These contracts have the potential to either unlock significant grid benefits or introduce new layers of complexity – the outcome depends on their thoughtful design.

7.3 Reshaping SIDS tariffs for grid modernisation

Clear and predictable access tariffs are essential for providing the economic signals necessary to guide investment in renewable energy projects that offer the greatest value. Transparency around these tariffs reduces investor risk and promotes the development of resources that not only produce clean energy but also actively contribute to flexibility, voltage support and other essential grid services. This alignment of incentives between investors, utilities and regulators is vital to ensure a cost-effective and sustainable energy transition in SIDS.

While well-designed incentive frameworks play a critical role in stimulating the deployment of diverse renewable energy solutions, these benefits can be significantly eroded by outdated tariff structures. Flat volumetric tariffs prevalent in many SIDS fail to accurately reflect the costs associated with grid operation and system expansion, particularly when integrating large amounts of variable renewables. Recovering fixed costs, particularly network-related expenses, through a simple per-kilowatt hour charge creates inefficiencies that are magnified by the integration of DERs and EVs. For example, some tariff reforms that would lead to high benefits with low implementation costs[4] (where smart meters are not needed) would include removing residual costs[5] from the volumetric components of the tariff and charging these costs through a fixed charge; and redesigning subsidies. Transitioning towards cost-reflective tariffs that accurately assign costs to their drivers is essential for guiding efficient consumption and sustainable DER deployment while ensuring full cost recovery. Time-of-use tariffs are optimal, providing the temporal granularity for price signals that align with system needs. Smart meters are critical to realise the full benefits of time-of-use tariffs. Even in SIDS without widespread smart metering, there are high-impact, low-cost tariff reforms that can be implemented:

- **Shift residual costs to fixed charges:** Removing fixed costs embedded within volumetric energy charges and recovering them through a distinct fixed-fee component enhances cost transparency and price signal accuracy.
- **Re-evaluate net metering:** Policies that offset retail energy charges through net metering lead to cost inequities and should be replaced with more equitable support mechanisms for DERs.
- **Redesign subsidies:** Subsidies should be decoupled from energy consumption. This decoupling can take the form of fixed incentives or rebates that promote efficient technology choices rather than indiscriminate energy use.

4 Based on the recommendations provided by the authors in MINEM, 2021.

5 Residual costs are costs that do not increase or decrease due to changes in consumption patterns. Since these costs cannot be assigned efficiently, they need to be recovered in the least distortive manner.

Box 5 highlights the definitions of the different tariffs and the design principles for tariff setting.

Box 5 Key tariff options and definitions

- Network tariff: A charge within the electricity bill designed to recoup the costs associated with transmission and distribution assets and their operation.
- Retail tariff: The end-user electricity rate that aggregates generation, network charges, ancillary services, retail margin and any applicable regulatory surcharges.
- Energy charge: The variable portion of the electricity tariff based on actual energy consumption (kWh).
- Capacity term (demand charge): A billing component based on a customer's capacity needs (kW). It can reflect contracted capacity, measured peak demand or a combination of the two.
- Fixed term: A recurring fixed charge on the electricity bill, often expressed on a monthly basis.

Tariff structures

- Volumetric tariff: A retail tariff where all costs are recovered through a single energy charge (kWh basis).
- Time-of-use tariff: A tariff with predefined periods where different rates apply. It could differentiate between on-peak, off-peak and shoulder periods.
- Flat tariff: A tariff without time-based differentiation, applying a constant rate regardless of when energy is consumed.

Tariff design principles

- Cost-reflectivity: A principle that tariff structures should align with the actual costs of providing electricity service, sending accurate price signals to customers to encourage efficient usage patterns.
- Additivity: A principle emphasising transparent tariff design where each retail tariff component reflects the sum of the underlying cost elements (generation, transmission, distribution, etc.), promoting cost clarity.

Net metering tariffs: Among the challenges posed by outdated tariff structures, the issue of net metering is a prime example of misaligned incentives in the evolving energy landscape. Net metering offers a simplified mechanism for encouraging distributed generation, particularly rooftop solar PV. However, its reliance on flat energy charges can perpetuate cost inequities and distort market signals. Under net metering, energy injected into the grid by a prosumer during periods of excess generation is netted against their energy withdrawals from the grid. This typically occurs over a defined time frame, such as a month. In simpler terms, all the prosumer's exported and imported energy during a billing cycle is netted, and the economic value of the exported energy is pegged to the retail tariff's energy charge. Exported and imported electricity are valued equally and ignores the time of the day value differences. The combination of net metering and the prevailing flat volumetric tariffs common in SIDS creates misaligned incentives for grid users with behind-the-meter generation. It also reduces revenue for utilitites and can introduce operational challenges, when excess generation is not regulated by the utility. Self-generation reduces the prosumer's payments to the utility but does not lessen the existing network infrastructure and policy costs. Where grid costs are recovered through energy-based tariffs, *i.e* based on the usage of the grid, net metering can bring in equity issues. These fixed costs are then shifted onto non-behind-the-meter customers, resulting in cost inequities. While widely adopted in the early stages of distributed solar development, net metering is not considered a sustainable long-term solution for power systems of any scale. Alternative policy approaches for self-generation are recommended for the long run. Moving forward, tariff structures should ensure prosumers contribute fairly to fixed costs such as transmission and distribution capacity charges.

7.4 Planning and capacity building to address grid modernisation in SIDS

SIDS often face complex administrative and regulatory processes that can hinder the swift deployment of critical grid modernisation initiatives. The unique challenges faced by islands demand a shift towards proactive planning strategies, specifically streamlining permitting processes and pre-empting the needs of advanced grid solutions. Anticipatory planning frameworks are crucial. Instead of reacting to individual DER integration proposals, SIDS would benefit from forward-looking master plans that proactively identify optimal locations for DER deployment and from sector coupling opportunities that consider grid capacity, land availability and community impacts. Such plans offer a roadmap for investors and developers, streamlining the permitting process and reducing unnecessary delays. Furthermore, predesigned technical standards for cutting-edge grid solutions facilitate timely and efficient approvals. Proactive standardisation of inverter specifications, microgrid interconnection rules, and cybersecurity requirements establish a clear pathway for technology adoption.

Building local skill development and knowledge sharing is vital to capitalise on the potential of new grid technologies. The introduction of DSM requires developing capacity-building initiatives, educating consumers to participate in the schemes, training utility staff to perform load profiling, and implementing smart metering and dynamic pricing mechanisms. Capacities to model and simulate systems with DERs should also be developed to ensure that system stability can be evaluated at critical moments and pre-emptive measures can be adopted for the same. Knowledge-sharing platforms, offering training, workshops and partnerships, facilitated through international collaborations, can support this effort.

Assessing existing skill sets and identifying gaps is key to building the workforce needed for grid modernisation in SIDS. Table 8 showcases the gaps in skill upgradation, for different stakeholders, towards grid modernisation.

Table 8 Gaps in skill upgradation

Stakeholder group	Existing skill sets	Skill requirements for grid modernisation
Utilities	SIDS utilities possess a strong foundation in operating conventional centralised power systems, maintaining transmission and distribution assets, and managing power flows within a largely unidirectional paradigm.	The transition to renewable grids demands a shift in both technical and operational skill sets. Utilities must develop expertise in integrating distributed generation with diverse characteristics (rooftop solar PV, microgrids, etc.), managing bidirectional power flows, leveraging energy storage for flexibility, and implementing demand response programmes. Proficiency in data analytics and predictive modelling will also be key for optimising asset utilisation and handling the increased variability of SIDS grids.
Regulators	Regulators in SIDS are well versed in traditional regulatory frameworks focusing on centralised generation, cost-of-service tariffs and system reliability.	Grid modernisation calls for a regulatory mindset that embraces innovation and flexibility. Regulators must become familiar with the economic and technical aspects of distributed energy resources, design performance-based incentives that reward system efficiency, and establish market mechanisms that allow for price signals that reflect real-time system conditions. Familiarity with cybersecurity risks and appropriate safeguards will be critical in the digitised energy landscape.
Government	Typically, government officials in SIDS prioritise strategic economic development, energy security and the implementation of comprehensive policy frameworks.	Policy makers must develop a nuanced understanding of the rapidly evolving grid technology landscape, including the potential of energy storage solutions and sector coupling (*e.g.* electrification of transport), as well as the role of grid modernisation in achieving broader climate goals. They will need to design targeted incentives, streamline permitting processes, and cultivate public awareness of both the benefits and responsibilities associated with the clean energy transition.
Private sector	The private sector in SIDS may currently possess expertise in project development, financing and technical knowledge focused on conventional power generation technologies.	Proficiency in a modernised grid environment necessitates expertise in the development of renewable energy projects, especially those appropriate for SIDS; the integration of energy storage solutions; and the design of demand response or load-shifting programmes that enable flexibility among consumers. Thorough knowledge of the distinct regulatory obstacles in SIDS, the capacity to establish successful collaborations between public and private sectors, and methods to reduce perceived risks for investors will be essential for attracting the necessary funds for modernisation.

Box 6 highlights the financing for the energy transition in Maldives, supported by policy and regulations, capacity building and finance mobilisation through the Climate Investment Funds' *Scaling Up Renewable Energy Program in Low Income Countries* (NREL, 2024).

Box 6 Financing the energy transition in Maldives

Maldives, an archipelago of 1200 islands, is working towards modernising its grid to enable the inclusion of renewable energy. This work is intended to meet the growing demand and reduce fossil fuel consumption. Enhancing stability and increasing the reliability of the island power system has been key, as the system is islanded and not interconnected. It was identified that battery energy storage systems could be a technology enabler that could solve multiple technical challenges and help achieve 70% renewable energy penetration by 2030. The government, supported by Climate Investment Funds, identified the key areas – such as risk mitigation, finance mobilisation, regulatory framework and technical capacity building – that required work for the transition to happen. It was identified that appropriate sizing and de-risking investment was needed to ensure private sector investment in solar PV and storage and key action points to be implemented include

- Regulatory framework: Development of utility guidelines for the licensing, installation, operation and policy directives for solar PV, with similar guidelines for battery energy storage systems to be developed soon.
- Technical assistance: Provision of training on all project phases to all stakeholders involved, including the project management unit, utility staff and regulators – on public and private asset ownership models, pricing models, deployment phasing, deployment of hybrid projects, and workforce reallocation. This training should enable stakeholders to handle and co-ordinate the deployment of renewables and storage.
- Finance mobilisation: Design of finance mechanisms to provide risk mitigation and incentives using different mechanisms, such as tariff buydown grants and secured payment mechanisms.

By prioritising capacity building, SIDS empower themselves to navigate the complexities of grid modernisation, ensuring that these modernisation initiatives deliver tangible and lasting benefits. Investing in a skilled workforce fosters technological independence, creates high-value employment opportunities and strengthens the resilience of island communities, laying the foundation for energy systems that are not only modern but truly sustainable.

7.5 Improving grid access and connection processes

SIDS often face challenges in the form of lengthy connection processes, limited grid transparency and unpredictable access tariffs for renewable energy projects. These factors can delay project timelines, increase costs and create a less favourable environment for developers and investors. To accelerate the integration of renewables into their power systems, SIDS need to address these procedural and informational barriers. Streamlining processes, providing clear grid data and establishing well-defined tariff structures will be crucial for creating a more efficient and attractive clean energy sector.

On an average, the process to get connection permits and network access takes up to one and a half years in SIDS, and sometimes longer. Reducing these time frames is crucial for successful renewable energy deployment. Improving the transparency of information in real time, in both the transmission and the distribution grid, is also highly recommended. Such improvement requires transparency in connection procedures and associated connection costs for different locations in the network. This information would help investors identify profitable opportunities in technologies that are beneficial to the system. Transparency is also crucial for optimising the incorporation of new renewable capacity, guaranteeing that projects comply with grid standards and maximise their impact on system stability.

The presence of bureaucratic obstacles can deter investor confidence and result in financial burdens for projects. Optimising these procedures by means of digitising applications, establishing well-defined timelines, and implementing single-window clearance mechanisms can greatly expedite project execution and foster a more appealing climate for investments in renewable energy.

Proactive grid planning, which includes the clear disclosure of network technical parameters, possible congestion points and planned reinforcements, would enable developers to make well-informed decisions regarding the feasibility and location of projects.

Table 9 provides insights based on different stakeholder perspectives from different countries on key considerations for streamlining permitting processes.

Table 9 Lessons learnt on permitting processes

Stakeholder	Perspectives on permitting processes	Lessons learnt from past studies
Government	Lengthy connection processes and a lack of transparent grid information pose serious challenges to a government's ability to meet its renewable energy targets and attract investment into the sector. These issues create inefficiencies, drive up project costs and erode confidence in the government's ability to create a conducive regulatory environment for a clean energy transition.	Needs: Strategic grid development aligned with renewable energy targets. Proactive planning that anticipates growth in variable renewable energy and sector coupling, prioritises investments in flexibility and capacity expansion. Actions: Develop comprehensive master plans for transmission and distribution upgrades. Implement policies and regulations to incentivise grid modernisation, flexibility solutions and the use of smart grid technologies.

Utilities	Cumbersome permitting timelines and unclear access tariff structures complicate utilities' planning processes and capacity expansion plans. Limited transparency about available grid capacity and potential constraints makes it difficult for utilities to effectively manage new connections and maintain system reliability while facilitating the integration of renewable energy.	Needs: Enhanced visibility into grid status, improved forecasting and the ability to manage distributed energy resources effectively. Actions: Invest in advanced monitoring systems, forecasting tools and communication infrastructure for real-time data exchange. Develop distributed energy resource interconnection standards and procedures to streamline the process.
Regulators	Regulators must reconcile the requirement for strong connection protocols with the pressing need to expedite the implementation of renewable energy infrastructure. The lack of clear grid information and the unpredictability of access fees impede their capacity to define equitable and transparent market mechanisms that facilitate the prompt connection of feasible renewable energy projects to the grid.	Needs: A regulatory framework that fosters grid modernisation, cross-sector coupling and flexibility investments while ensuring fair cost recovery mechanisms for utilities. Actions: Establish performance-based regulation that rewards utilities for system reliability and VRE accommodation. Revise tariff structures to incentivise demand-side management and incorporate the cost of flexibility services.
Project developers	The time, cost and risk associated with project development are significantly increased by the protracted permitting processes that project developers must navigate. Uncertainty is generated by the limited availability of transparent information regarding grid constraints, connection rules and connection costs, which may result in suboptimal project siting decisions and impede project feasibility assessments.	Needs: Technical assistance for grid integration studies, transparent and predictable tariff structures, grid connection rules and streamlined connection processes. Actions: Work collaboratively with utilities and regulators to identify grid reinforcement needs and advocate for policies that facilitate timely and cost-effective grid connections.
Financial sector	Banks and other financial institutions often view lengthy permitting processes and uncertainty around grid capacity and tariffs as additional risks when evaluating renewable energy projects in SIDS. This can lead to higher financing costs or even reluctance to invest, limiting the availability of capital for critical clean energy infrastructure.	Needs: Access to grid development plans and a regulatory environment that supports timely and cost-effective grid investments. Actions: Collaborate with governments, utilities and regulators to identify and de-risk grid infrastructure projects that are critical for renewable energy integration. Develop financing mechanisms tailored to the specific needs of SIDS grids.

7.6 Balancing equity and efficiency in SIDS subsidy reform

Subsidies are embedded in the electricity pricing structures of SIDS. However, the design of these subsidies can often distort market signals that guide consumption behaviour. When subsidies depress the retail prices faced by consumers below the true cost of electricity, they reduce the economic value of energy and can even encourage inefficient use. Additionally, subsidies skew the economic viability of DERs such as rooftop solar PVs or energy storage. Furthermore, distorted price signals can discourage investments in distributed generation, like rooftop solar PV, as the perceived financial benefits become less attractive. Without accurate pricing, the true benefits these resources offer in terms of grid flexibility, voltage support and reduced reliance on imported fuels are obscured, hindering their widespread adoption.

A redesign of subsidies aligned with the broader energy goals is key. This hinges on two key principles:

- **Targeted assistance:** Rigorous testing should ensure subsidies are directed exclusively to those households with demonstrated need, typically low-income or vulnerable segments of the population.
- **Price signal integrity:** Maintaining accurate price signals that reflect the true cost of electricity is paramount.

Distorted price signals caused by poorly designed subsidies act as a barrier to grid modernisation in SIDS. Artificially low electricity prices suppress the motivation for energy efficiency measures. This creates an unnecessarily heightened demand burden on the grid, complicating efforts to optimise infrastructure investments and integrate renewable generation.

The “transfer-in-cash” model offers a solution: a baseline level of consumption is deemed subsidy eligible, with households receiving direct compensation (as cash or credit) to offset this cost. Importantly, this approach leaves the tariff structure intact, meaning that any consumption beyond the subsidised baseline is charged at full cost, encouraging efficiency. This approach to subsidies has seen successful implementations in countries like France, Italy and the United Kingdom. The transfer-in-cash scheme can ensure the provision of subsidised electricity to those in need, while ensuring that others pay the actual value for electricity. This can ensure that consumption patterns become more responsive to price, encouraging efficient use and reducing peak demand strain on the grid. Accurate pricing, reflecting the contribution of DERs to system support, such as balancing supply and demand and improving reliability, will enable the smoother integration of these resources.

7.7 Financing grid modernisation in SIDS

Despite their vulnerability to climate change, SIDS often struggle to attract the capital flows needed for grid modernisation. Investors remain wary due to the small market size, the unfamiliar regulatory regimes and the perceived risks of integrating new technologies into island power systems. Innovative financing solutions are therefore essential.

Traditionally, economic models have focused on large-scale projects and have failed to address the distributed nature of SIDS energy systems. Blended financing, public-private risk-sharing mechanisms and a shift from subsidies to revenue-generating models are needed. Grid modernisation is a complex, capital-intensive undertaking involving infrastructure upgrades and technology deployment to aid the integration of new generation assets. Strategic financial planning and channelling of capital from diverse sources – multilateral donors, development finance institutions and the private sector – and aligning financing with long-term energy security and sustainability targets can support.

Strategic priorities for attracting investment in grid modernisation in SIDS

- **Mitigating risks:** The perceived risk for investors in SIDS is a critical factor in impeding private capital flows into SIDS grid modernisation. Factors like limited market size, unfamiliarity with local regulatory environments, and concerns about the technical capacity to handle the integration of new grid technologies contribute to risks. Risk mitigation strategies, such as credit enhancement mechanisms, guarantees or partial risk insurance, can offset potential losses and provide a safety net for investors. A clear and predictable regulatory framework, along with streamlined contracting processes, reduce uncertainties and increase the bankability of projects. Offering technical assistance to SIDS utilities and project developers enhances their ability to prepare well-structured proposals that meet the due diligence standards of international financiers. These measures, combined with a strong track record of successful pilot projects, can significantly shift investor perceptions and unlock the capital needed to scale up transformative grid modernisation initiatives.
- **Using blended finance:** Blending funding sources is crucial for maximising the impact of limited public resources and catalysing large-scale investment in the grid infrastructure. Blended finance models, where public funds are used to de-risk investments or provide first-loss capital, are vital for attracting private financing into DER projects, microgrid solutions and smart grid technology that would otherwise be deemed too risky for SIDS markets. Green finance instruments, such as green bonds or sustainability-linked loans, can tap into the growing pool of investors seeking to align their portfolios with the clean energy transition, specifically supporting projects with demonstrated resilience and climate adaptation benefits. By carefully combining these instruments in a way that matches technological needs, addresses project risk profiles and aligns with the priorities of SIDS energy plans, these limited budgets can be stretched further to achieve the required scale of grid infrastructure modernisation.
- **Building the business case:** The business case for grid modernisation must shift from reliance on subsidies to a model where investments generate direct revenue streams, ensuring long-term sustainability. Modern DERs, advanced grid control systems, sector coupling and demand-side flexibility programmes offer new opportunities for value creation. Performance-based payments for ancillary service provision, such as frequency regulation, voltage support and black-start capabilities, can ensure remuneration for project owners. Additionally, sector coupling, through the electrification of transport, water desalination, or other sectors, can unlock new markets for excess renewable generation. Recognising and quantifying the economic value of these grid services and potential revenue streams within tariff structures and project financing models is essential. This approach transforms grid modernisation investments from mere cost centres into assets with the potential to generate financial returns, enhancing their attractiveness to a wider range of investors.
- **Ensuring sustainability:** Empowering local financial institutions within SIDS is essential for creating self-sustaining financing ecosystems for grid modernisation. While these institutions may have limited experience with renewable energy or advanced grid technologies, targeted capacity-building initiatives can bridge this gap. Technical assistance programmes focused on evaluating the viability of DER solutions, understanding the nuances of grid integration, and developing project-specific financing products are crucial. Development banks can play a vital role in facilitating knowledge transfer and fostering partnerships between local institutions and international financiers with grid expertise. This collaboration can accelerate the adoption of financing models like mini-grid lease financing,[6] on-bill financing for energy efficiency upgrades, and pay-as-you-go schemes for smart meter systems. By empowering local financial institutions to become active lenders and facilitators, SIDS can ensure the long-term availability of capital tailored to the specific needs and scale of their grid modernisation efforts.

6 Mini-grid lease financing - where the ownership and operation of the mini-grid are subject to a leasing arrangement and the operator leases the assets of the minigrid from the financier rather than purchasing them.

- **Tailoring finance:** Financing solutions tailored to SIDS realities are paramount for unlocking the full potential of grid modernisation. Approaches that work in larger markets often require adaptation to the smaller scale of SIDS projects. Appropriate approaches may include designing pay-as-you-go financing models for rooftop solar PVs and energy efficiency solutions, enabling microfinancing for community microgrid projects, and developing community ownership structures for larger DER installations. These models address the issue of affordability while empowering local actors to participate in their energy transition. Additionally, financing schemes must align with the technical, geographic and social complexities of island grids. This may require innovative solutions for ensuring equitable access to financing benefits across different stakeholder groups within SIDS.

7.8 Strategic partnerships for island-wide consumer led flexibility programmes

The unique energy landscape of SIDS, often characterised by the presence of a few large energy consumers, demands a tailored approach to consumer engagement. Actively partnering with industries, hotels and other high-consumption entities presents a key opportunity for island-wide flexibility programmes, significantly amplifying their impact and overall efficacy. Large energy consumers in SIDS can make substantial contributions to grid stability. Their sizeable loads often offer untapped flexibility that can be harnessed through targeted demand response programmes. Table 10 highlights the flexibility actions that could be taken by different types of customer and the associated grid benefits.

Incentivising these stakeholders to adjust their consumption patterns during peak periods or in response to grid disturbances makes available the resources that are essential for balancing and ensuring the reliability of the system in the presence of VRE.

Table 10 Flexibility service provision from different consumers

Consumer type	Flexibility actions	Grid benefits
Tourism (resorts)	Modulating heating, ventilation and air-conditioning; pre-cooling pools; using thermal storage; adjusting desalination schedules	Peak demand reduction, voltage support, flexibility during outages
Industrial (mining/ processing)	Adjusting production schedules, using on-site generation/co-generation (if present), optimising pumping systems	Smoothing of load curves, frequency regulation, black-start capabilities
Commercial (ports)	Pre-cooling refrigerated containers, smart scheduling of ship charging, shore-to-ship power	Load shifting, demand reduction during peak tourist seasons, ancillary services
Agricultural (irrigation)	Smart scheduling of water pumping, using on-farm energy storage (if available) and exploring agrivoltaics options.	Peak shaving, addressing seasonal demand peaks, supporting microgrid integration

Effective implementation of such programmes depends on cultivating collaborations and establishing open communication channels among utilities, policy makers and major consumers. This communication facilitates the creation of mutually advantageous initiatives that acknowledge the operational needs of the grid and the commercial demands of these key stakeholders. Transparency, in conjunction with performance-based remuneration systems, is crucial in obtaining their involvement and guaranteeing the sustained feasibility of these flexibility initiatives. This collaborative approach showcases the potential for collective action in tackling SIDS-specific energy challenges, transforming consumers into active partners in achieving island-wide energy security and sustainability.

8 References

AEMO (2023), *Inertia in the NEM explained*, AEMO, www.aemo.com.au/-/media/files/initiatives/engineering-framework/2023/inertia-in-the-nem-explained.pdf

BREA (2025), "Renewable Energy Grid Stability Challenges", Barbados Renewable Energy Association, https://brea.bb/renewable-energy-grid-stability-challenges/

Dietrich, K., *et al*. (2012), "Demand Response in an Isolated System With High Wind Integration", *IEEE Transactions on Power Systems*, vol. 27/1, pp. 10.

DigSILENT PowerFactory (2023), *Repurposing existing generators as synchronous condensers*, https://arena.gov.au/assets/2023/06/repurposing-existing-generators-as-synchronous-condensers-report.pdf

DNV GL (2018), *Formulation of National Electricity Grid Code for Seychelles – Grid Code*, https://res4africa.org/wp-content/uploads/2023/04/RegulatoryReviewofElectricityMarketinSeychelles.pdf

Egido Cortés, I., *et al*. (2016), *Store: a comprehensive research and demostration project on the application of energy storage systems in island power systems*, Comillas Universidad Pontifica, https://repositorio.comillas.edu/xmlui/handle/11531/14262

EirGrid (2022), *System and Renewable Summary Report*, www.eirgridgroup.com/site-files/library/EirGrid/System-and-Renewable-Data-Summary-Report.xlsx

EirGrid and SONI (2018), S*ystem Non Synchronous Penetration Definition and Formulation*, www.eirgridgroup.com/site-files/library/EirGrid/SNSP-Formula-External-Publication.pdf (accessed 12 November 2020).

EirGrid and SONI (2014), *Delivering a Secure, Sustainable Electricity System (DS3): Programme Overview*, www.eirgrid.ie/ds3-programme-delivering-secure-sustainable-electricity-system

Ember (2025), "The Philippines", https://ember-energy.org/countries-and-regions/philippines-the/

Energy Regulatory Commission (2016a), *Philippine Grid Code*, https://policy.asiapacificenergy.org/sites/default/files/PGC2016Edition%28ResolutionNo22Seriesof2016%29.pdf

Energy Regulatory Commission (2016b), "Resolution Approving Publication of Philippine Grid Code 2016 Edition", https://jurisprudence.ph/laws/a-resolution-approving-the-publication-of-the-approved-philippine-grid-code-2016-edition

EU (2023), *Clean energy for EU Islands - Study on regulatory barriers and recommendations for clean energy transition on EU Islands*, https://op.europa.eu/en/publication-detail/-/publication/1b609b6b-9e33-11ed-b508-01aa75ed71a1/language-en

Fraunhofer (2016), "Better Forecasting For Solar And Wind Power Generation", www.fraunhofer.de/en/press/research-news/2016/June/better-forecasting-for-solar-and-wind-power-generation.html

Hatziargyriou, N., *et al*. (2021), "Definition and Classification of Power System Stability – Revisited & Extended", *IEEEE Transactions on Power Systems*, vol. 36/4, pp. 3271-3281, https://doi.org/10.1109/TPWRS.2020.3041774

IEA (2018), *Recommended Practises for Wind and PV Integration Studies*, International Energy Agency, Paris, https://iea-pvps.org/key-topics/recommended_practises_for_wind_and_pv_integration_studies/

IRENA (2013), *Assessment of the Dynamic Grid Stability in the Island of Palau,* International Renewable Energy Agency, Abu Dhabi, unpublished.

IRENA (2015a), *Grid Stability Assessment for the Upolu Island – Samoa,* International Renewable Energy Agency, Abu Dhabi, unpublished.

IRENA (2015b), *Study on the Integration of Renewable Energy in Aitutaki*, International Renewable Energy Agency, Abu Dhabi, unpublished.

IRENA (2015c), *Study on the Integration of Renewable Energy in Antigua*, International Renewable Energy Agency, Abu Dhabi, unpublished.

IRENA (2016a), *Extension of the Grid Integration Study for the Island of Upolu in Samoa*, International Renewable Energy Agency, Abu Dhabi, unpublished.

IRENA (2016b), *Scaling up variable renewable power: The role of grid codes*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Grid_Codes_2016.pdf

IRENA (2018a), *Grid Integration Study: Renewable Energy Strategy for Viti Levu, Republic of the Fiji Islands, unpublished*, International Renewable Energy Agency, Abu Dhabi, unpublished.

IRENA (2018b), *Transforming small-island power systems: Technical planning studies for the integration of variable renewables*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Jan/Transforming-small-island-power-systems

IRENA (2019a), *Grid integration study: Renewable energy strategy for Espiritu Santo, Vanuatu*, International Renewable Energy Agency, Abu Dhabi, unpublished.

IRENA (2019b), *Innovation landscape brief: Behind-the-meter batteries*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_BTM_Batteries_2019.pdf

IRENA (2019c), *Innovation landscape brief: Utility scale batteries*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf

IRENA (2019d), *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future

IRENA (2019e), *Innovation landscape brief: Aggregators*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Publication/2019/Feb/IRENA_Innovation_Aggregators_2019.pdf

IRENA (2019f), *Demand-side flexibility for power sector transformation,* International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2019/Dec/Demand-side-flexibility-for-power-sector-transformation

IRENA (2019g), *Innovation landscape brief: Renewable power-to-hydrogen*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Power-to-Hydrogen_Innovation_2019.pdf

IRENA (2019h), *Innovation landscape brief: Flexibility in conventional power plants*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Flexibility_in_CPPs_2019.pdf

IRENA (2019i), *Innovation landscape brief: Electric vehicle smart charging*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_EV_Smart_Charging_2019.pdf

IRENA (2019j), *Innovation landscape brief: Innovative ancillary services,* International Renewable Energy Agency, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovative_ancillary_services_2019.pdf

IRENA (2020), *Grid Assessment Study: The Dominican Republic*, International Renewable Energy Agency, Abu Dhabi, unpublished.

IRENA (2022), *Grid codes for renewable powered systems*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2022/Apr/Grid-codes-for-renewable-powered-systems

IRENA (2025), *SIDS Lighthouses Initiative: Progress and way forward*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/Publications/2025/Jan/SIDS-Lighthouses-Initiative-Progress-and-way-forward

Kundur, P., *et al*. (2004), "'Definition and classification of power system stability' IEEE/CIGRE Joint Task Force on Stability Terms and Definitions", *IEEE Transactions on Power Systems*, vol. 19/3, pp. 1387–401, https://doi.org/10.1109/TPWRS.2004.825981

Kundur, P.S. (1994), *Power System Stability and Control*, McGraw-Hill, New York.

Lin. Y., *et al*. (2020), *Research Roadmap on Grid-Forming Inverters*, National Renewable Energy Laboratory, Golden, CO, https://docs.nrel.gov/docs/fy21osti/73476.pdf

Liu, K., *et al*. (2018), "Avoiding Frequency Second Dip in Power Unreserved Control During Wind Power Rotational Speed Recovery", *IEEE Transactions on Power Systems*, vol. 33/3, pp. 9.

Marinescu, B., *et al*. (2022), "Dynamic Virtual Power Plant: A New Concept for Grid Integration of Renewable Energy Sources", *IEEE Access*, vol. 21/1, pp. 15.

Masood, N.-A., *et al*. (2016), "Post-retirement utilisation of synchronous generators to enhance security performances in a wind dominated power system", *IET Generation, Transmission & Distribution*, vol. 10/13, pp. 8.

MINEM (2021), *Modernization of the Peruvian electricity system. Pillar 3: Innovation in distribution and retail*, Ministry of Energy and Mines, Lima, www.minem.gob.pe/minem/archivos/Theme 3-Innovation in Distribution and Retail Market-Final Report-20210624.pdf

Ministerio de Industria, Energía y Turismo (2023), "Royal Decree 738/2015, of July 31, which regulates the activity of electrical energy production and the dispatch procedure in the electrical systems of non-peninsular territories", www.boe.es/eli/es/rd/2015/07/31/738/con

Ministry of Energy and Public Utilities (2022), *Renewable Energy Roadmap 2030 for the Electricity Sector - Review 2022*, Republic of Mauritius.

Morren, J., *et al*. (2006), "Wind turbines emulating inertia and supporting primary frequency control", *IEEE Transactions on Power Systems*, vol. 21/1, pp. 2.

Munster, M., *et al*. (2020), "Sector Coupling: Concepts, Potentials and Barriers", *AEIT International Annual Conference*, pp. 6.

NationalGrid ESO (2021), *Stability Pathfinder Phase 2: Expressions of Interest Final Assessment Methodology*, www.nationalgrideso.com/document/197046/download

NationalGridESO (2022), *Stability Market Design*, www.nationalgrideso.com/document/247941/download

NREL (2015), *Renewable Energy on the Grid - Redefining What's Possible*, National Renewable Energy Laboratory, https://docs.nrel.gov/docs/fy15osti/63367.pdf

NREL (2020), *Inertia and the Power Grid: A Guide Without the Spin*, National Renewable Energy Laboratory, https://docs.nrel.gov/docs/fy20osti/73856.pdf

NREL (2024), *Battery storage unlocked: Lessons learned from emerging economies*, National Renewable Energy Laboratory, https://docs.nrel.gov/docs/fy25osti/91781.pdf

Ofgem (2022), *Grid Code (GC) GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine (VSM) Capability) (GC0137)*, www.ofgem.gov.uk/sites/default/files/2022-01/GC0137%20Authority%20Decision.pdf

Palensky, P., and Dietrich, D. (2011), "Demand side management: Demand response, intelligent energy systems, and smart loads", *IEEE Transactions on Industrial Informaticsd*, vol. 7/3, pp. 8, https://doi.org/10.1109/TII.2011.2158841

Red Electrica (2023), "The Spanish Electricity System", www.sistemaelectrico-ree.es/en/spanish-electricity-system

SEV (2025), "Pumped storage", www.sev.fo/english/projects/pumped-storage

Sigrist, L., *et al*. (2017), "Economic assessment of smart grid initiatives for island power systems", *Applied Energy*, vol. 189, pp. 12.

Taibi, E., and Fernández, C. (2017), "The impact of electric vehicles deployment on production cost in a Caribbean Island Country", *Proceedings of the 1st E-Mobility Power System Integration Symposium*, Berlin, Germany.

Tróndheim, H. M. (2022), "Ensuring Supply Reliability and Grid Stability in a 100% Renewable Electricity Sector in the Faroe Islands", Aalborg Universitetsforlag, https://vbn.aau.dk/files/549497108/phd_HMT_e_pdf

Tróndheim, H. M., *et al.* (2022), "Frequency and Voltage Stability Towards 100% Renewables in Suðuroy, Faroe Islands", *Cigre Science & Engineering*, Vol. 25, https://vbn.aau.dk/files/519719625/CSE_25_frequency_and_voltage_stability_towards_100_renewables_in_suduroy_faroe_islands.pdf

UNECA (2021), *Regulatory Review of the Electricity Market in Seychelles: Towards Crowding-in Private Sector Investment*, United Nations Economic Commission for Africa, https://res4africa.org/wp-content/uploads/2023/04/RegulatoryReviewofElectricityMarketinSeychelles.pdf

USAID (2019), *Promoting Transparency and Public Participation in Energy Regulation: A Communications Primer for Utility Regulators*, US Agency for International Development, https://pubs.naruc.org/pub/F358864A-0EC2-9185-D0B5-5A6B9C13BEA6

IRENA

International Renewable Energy Agency