TRANSFORMING SMALL-ISLAND POWER SYSTEMS

TECHNICAL PLANNING STUDIES FOR THE INTEGRATION OF VARIABLE RENEWABLES

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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**

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FOREWORD

Small Island Developing States (SIDS) face a range of pressing challenges, from coping with the effects of climate change to dependence on costly fuel imports to meet their energy needs. To address these challenges, SIDS have resolved to harness their vast renewable energy potential, with a view to strengthening climate resilience and improving energy security.

Today, SIDS are at forefront of global efforts to tackle climate change and to make the transition to a sustainable energy future. A growing number of SIDS are striving for 100% renewable systems in the foreseeable future.

With the steady cost decline of renewable-based technologies, SIDS have started transforming their power systems with increasing shares of solar and wind energy, thus reducing their energy import bills, creating local employment and powering sustainable economic growth. Integrating high shares of variable renewables into power systems is no longer a distant aspiration, but an exciting reality. Challenges, however, remain, including numerous technical barriers and the lack of local capacity to plan, operate and maintain these systems

The International Renewable Energy Agency (IRENA) works with SIDS to support their efforts to accelerate their energy transformation through the SIDS Lighthouses Initiative. In this context, the Agency supports SIDS in developing renewable energy roadmaps; provides policy and regulatory advice; supports project development; facilitates access to finance; and encourages the exchange of best practices

IRENA also works with SIDS on assessing their system capacity to integrate variable renewables, both through support for grid-integration studies and by helping to outline ambitious, yet achievable, penetration targets. Building local capacity to plan, operate and maintain more flexible power systems is key in this regard.

Transforming Small-island Power systems: Technical planning studies for the integration of variable renewables, highlights technical studies that can assist SIDS power system operators, particularly in identifying the technical challenges that must be addressed to integrate high shares of solar and wind energy, while considering system specificities, available resources and the need to maintain a secure and reliable power system. It outlines effective solutions, both at operational and expansion planning stages.

Building on the wealth of experience and knowledge gained by IRENA in its work with SIDS in recent years, this technical guide lays out viable options to transform the power systems of SIDS and maximise their renewable energy potential.

Adnan Z. Amin
Director-General
International Renewable Energy Agency

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ABBREVIATIONS

ANSI	American National Standards Institute
CCT	Critical clearing time
DLR	Dynamic line rating
DMS	Distribution management system
EENS	Expected energy not served
ELCC	Effective load-carrying capacity
EMS	Energy management system
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	Flexible alternating current transmission systems
FRT	Fault ride through
GPS	Global positioning system
GWh	Gigawatt-hour
HVRT	High-voltage ride through
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPP	Independent power producer
IRENA	International Renewable Energy Agency
kW	Kilowatt
kWh	Kilowatt-hour
LOLE	Loss of load expectation
LVRT	Low-voltage ride through
MW	Megawatt
MWh	Megawatt-hour
OVLS	Over-voltage load shedding
PMU	Phasor measurement unit
PPA	Power purchase agreement
PV	Photovoltaic
SIDS	Small Island Developing State
SpPS	Special protection scheme
SyPS	System protection scheme
STATCOM	Static synchronous compensator
T&D	Transmission and distribution
UCED	Unit commitment and economic dispatch
UFLS	Under-frequency load shedding
USD	United States dollar
UVLS	Under-voltage load shedding
VoLL	Value of lost load
VRE	Variable renewable energy

EXECUTIVE SUMMARY

The world's 57 **Small Island Developing States (SIDS)** share similar geographical, economic and environmental challenges.

Many have started to **integrate renewables into their electricity supply mix** or plan to do so soon. Due to the particular geographical and socio-economic context of SIDS, important benefits are expected to be achieved with this transformation. These include, in particular, **reducing dependency on fossil fuel imports**, which many SIDS now rely on for power generation.

Achieving such a transition depends, among other factors, on the **ability of the local power system to integrate renewable energy technologies** while maintaining adequate levels of security and reliability. Such integration intensifies the **technical challenges** that SIDS already face in operating their power systems, especially if high penetrations of variable renewable energy (VRE) sources, such as solar photovoltaic (PV) and wind power, are targeted.

How can utilities or regulators determine the level of VRE that existing power systems can accommodate, without major investments and within realistic operational limits?

Utilities in SIDS, therefore, must carry out **planning studies** while integrating VRE, in order to identify potential technical challenges and suitable preventive or corrective solutions. Failing to successfully carry out technical planning activities might result in slower VRE deployment, in the need to invest in expensive retrofitting of network assets, in lower reliability of the power system and in having to curtail VRE production (impacting investment profitability). Expanding power systems in SIDS and operating them with **high shares of VRE** calls for thorough planning and well-informed selection of **suitable technical solutions**.

The International Renewable Energy Agency (IRENA) has produced a guide to assist in such decision making.

Transforming small-island power systems: Technical planning studies for the integration of variable renewables highlights:

- the **expected challenges** associated with VRE integration in SIDS;
- the **VRE integration planning** required to overcome technical challenges, the technical studies needed to analyse and quantify such challenges, and how to carry out these studies;
- the **solutions required** to overcome VRE integration challenges.

Technical challenges of integrating variable renewable energy

The basic principle for power system operation and planning is to deliver electricity to the final consumer at least cost while meeting pre-defined criteria in terms of reliability and quality of service. Historically, power systems in SIDS have been based mostly on conventional generation such as diesel and hydropower generation. Together with the network infrastructure, conventional generators provided all of the services required to operate the system at given reliability and power quality levels.

VRE technologies have different characteristics than conventional generators and can bring new challenges when integrated into the electricity supply mix. VRE technologies refer to electricity generators with a variable power output that depends on the availability of the underlying primary renewable energy source. Solar PV and wind power are the main technologies that are traditionally considered to be VRE.

Because the output of VRE generators is difficult to control (except for curtailment actions) and difficult to predict with high accuracy, VRE technologies are more challenging to integrate into power systems as compared to other technologies, such as conventional fossil-fuelled generators or dispatchable renewable generators (*e.g.*, biomass, geothermal and reservoir hydropower).

What are the main technical issues to be investigated, and what studies are needed to find the maximum hosting capacity for VRE in a given system?

The main technical challenges that may arise when integrating high shares of VRE in island power systems are described as follows:

- **Ensuring sufficient firm capacity**, to ensure that the generation fleet will still be able to reliably supply the electrical load at all times. This capability is referred to as generation adequacy.
- **Addressing flexibility needs**, in order to accommodate the intraday variations (from minutes to hours) of the net load [3] with the generation system. This challenge is driven mostly by the variability and uncertainty of VRE.
- **Ensuring system stability**, which is a major technical concern when targeting high shares of VRE in small power systems. Since the electro-mechanical characteristics of the system often change significantly with high penetration of VRE, the response of the system to disturbances also changes, which could affect system operation.
- **Compliance with physical limits**, including the thermal capacity of lines, cable, transformers and other network elements. Integrating a large amount of VRE (or other power plant types) into the network (at the transmission or distribution level) can lead to power flows for which the system was not initially designed. There is thus a risk of exceeding the thermal capacity of network elements either in normal operating conditions or following an outage, when some network elements become unavailable.
- **Ensuring effective functioning of protection systems**, which are designed to prevent short circuits on the grid. VRE sources that connect to the grid through power electronics-based interfaces have limited short-circuit currents when compared to conventional power plants equipped with synchronous generators. High penetration of VRE may therefore lead to reduced short-circuit currents. Given that protection systems are generally set and co-ordinated to isolate faults for high short-circuit currents, there is a risk that they might not operate properly under massive presence of VRE.

3 Electricity demand minus the generation from VRE sources at a given time.

- **Maintaining power quality**, as defined within acceptable limits. In certain conditions, the integration of power electronics-based VRE sources (*e. g.*, solar PV) can lead to power quality issues due to the characteristics of these devices.

Use of planning to overcome technical challenges

Ensuring proper operation of the power system with the integration of VRE requires planning. The planning process normally is based on specific technical and economic studies using modelling and decision-support tools. This guide focuses on the technical component of the planning studies, which are the basis for establishing an adequate technical framework. A strong technical framework is one of the pillars, along with financial and institutional frameworks, for the successful deployment of large shares of renewable energy in a power system.

Characteristics of SIDS power systems for variable renewable energy integration planning

The first step when conducting technical studies to plan for the integration of VRE is to acquire a good understanding of the characteristics of the power system being studied and of the electricity sector of the island more generally.

The main characteristics of power systems in SIDS that need to be understood when planning for the integration of VRE are:

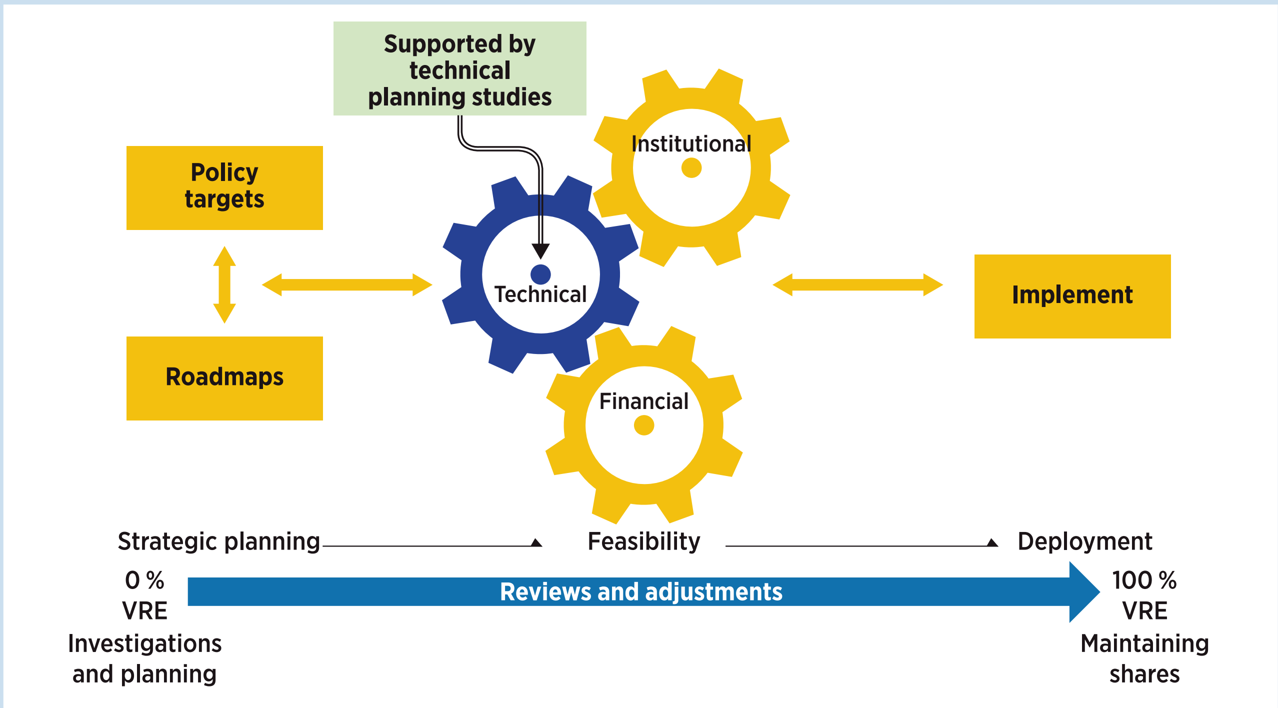
- **Flexibility of the existing and future power generation fleets.** Systems with high flexibility generally can be considered to be less sensitive to VRE integration, given that their generation can be controlled on demand to avoid such issues. Most island power systems rely on diesel generators for their electricity supply. These types of generators are generally very flexible, with high ramping capabilities, short start-up/shutdown times and low technical minimum (allowing them to operate at part load).

- **Demand and load profile.** The correlation between the system load and the expected VRE generation profiles is a key factor for VRE integration. This allows for determining the net load that needs to be supplied by the other non-VRE generators. Critical points are the level of the minimum load in the system and its period of occurrence in comparison with VRE production. Also crucial is the presence of sharp increases or decreases in load levels over time, and the effects that integration of VRE generation could have on these.

- **Structure and strength of transmission and distribution networks.** Electrical networks in SIDS can vary from very simple networks, with only a few medium-voltage distribution feeders, to larger systems including a high-voltage transmission grid and possibly interconnections with other systems. The network structure is a key element for the selection of the studies that need to be carried out to plan the system for VRE integration (see Figure ES1).

What are the possible ways to increase hosting capacity in the near and long terms, up to a given VRE target share?

Figure ES1: The role of technical planning studies in the transformation of SIDS power systems



- **VRE implementation strategy and generation expansion plans.** Will dispatchable (possibly thermal) generators be replaced with VRE? What is the future mix of VRE technologies expected in the system? What is the future geographical location of VRE generators in the network? In an ideal planning process, these aspects should already be considered when defining the generation expansion scenarios, as part of a comprehensive generation expansion plan.

- **Operational and planning practices of utilities in SIDS.** The operational and planning practices of utilities in SIDS have to be understood, as these may be limiting the integration of VRE. Defining the expansion and operational planning rules that allow for safe integration of VRE is a pre-requisite to succeed in power system transformation.

- **The influence of governance on technical operations.** The organisation of the electricity sector, the electricity market design (if any) and the associated regulatory framework all affect the ability of the power system to accommodate high shares of VRE.

What mitigation strategies would work best, considering possible infrastructure investments as well as operational measures and technical requirements for VRE-based power generators?

Table ES1: Mapping of power system characteristics with technical challenges of VRE integration

	Integration challenge					
System characteristic	**Generation adequacy**	**Intraday flexibility**	**Stability**	**Static thermal/ voltage grid limits**	**Short circuits and protections**	**Power quality**
Flexibility of existing and future power generation fleet	Medium Impact	Medium Impact	High impact	Medium Impact	Low or no Impact	Low or no Impact
Demand and load profile	High impact	High impact	High impact	High impact	Low or no Impact	Low or no Impact
Structure and strength of transmission and distribution networks	Medium Impact	Medium Impact	High impact	High impact	High impact	Medium Impact
VRE implementation strategy and generation expansion plans	High impact	High impact	High impact	High impact	High impact	Medium Impact
Expansion and operational planning	High impact	High impact	High impact	High impact	High impact	Medium Impact
Influence of governance on technical operations	High impact	High impact	High impact	High impact	High impact	Medium Impact

Legend: High impact | Medium Impact | Low or no Impact

All small-island power systems have their own specificities and should be treated as a particular case when planning for the integration of VRE. Table ES1 illustrates the relation between the technical challenges of VRE integration and the power system characteristics, highlighting the impacts of each.

Power system planning in SIDS

Power system technical planning can be divided into two categories, based on both the time horizons covered and the types of decisions that this planning supports:

- **Expansion planning** (long-/mid-term; month to years ahead): Power system expansion planning deals with mid- and long-term horizons, aimed at determining the future expansion investment, at least possible cost, required in the power system to supply the forecasted demand while complying with techno-economic and environmental constraints.

- **Operational planning** (short-term; day to week ahead): The main task of operational planning is to determine the optimal generation schedule for the upcoming operation period. Deployment of new equipment is not possible at this stage due to the short-term nature of this planning process. In this case, the only available means to set up the system operation are the control variables of the generating units (active and reactive power), transformers (tap position), reactor and capacitor banks (taps) and network topology (network switching).

Expansion and operational planning activities in a power system are **tightly linked**. Inadequate expansion planning may lead to several technical constraints for system operation, resulting in poor quality and in less affordable service provision. The same is valid for operational planning, which should ensure adequate feedback (return of experience) from system operation to the expansion planning process, with the objective of solving actual system constraints by means of appropriate future investments.

Planning small-island power systems is a challenging task because of the limited primary resources available for new generating units, the environmental constraints on network expansion, the high uncertainty in electricity demand growth and the small size of the system (meaning that any change to the system has a great impact on its overall performance). Furthermore, planning for VRE integration requires understanding the potential technical challenges derived from this integration.

These challenges can be **better understood and quantified** by means of **technical studies** conducted in a logical order. Several types of study are examined for this purpose:

- **Load and generation balance:**
  - Generation adequacy
  - Sizing of operating reserves
  - Generation scheduling.

- **Network studies**
  - **Static network analyses:**
    - Load flow studies
    - Static security assessment
    - Short-circuit current studies
  - **System stability analyses:**
  - Transient stability analysis
  - Frequency stability analysis
  - Voltage stability analysis
  - **Special network analyses:**
    - Defence plans
    - Grid connection studies.

The studies presented in the guide address various technical challenges of VRE integration through **well-defined methodologies** that can be repeated over time and used in different contexts of VRE integration. The guide also provides discussion of the typical time horizons (*i. e.*, expansion planning or operational planning) at which the different technical studies are generally performed (see Table ES2), as well as of the technical challenges addressed by each type of study (see Table ES3).

These various studies for VRE integration should not be seen as one-off activities, but rather as **continual or recurrent processes**, with iterative learning, given the dynamic nature of VRE deployments over time.

The ultimate purpose of these studies is to **support decisions** that can be made at the planning stage. The aim is to avoid technical issues in real-time operation or frequent activation of remedial actions (such as load shedding), which could be expensive or detrimental for consumers.

Table ES2: The main types of studies to support VRE integration

			Typical time horizon		Parts of the power system represented		
			Long-/mid-term planning (month to years ahead)	**Operational planning (day to week ahead)**	**Load and generation**	**Transmission**	**Distribution**
Generation adequacy			Almost always applicable	Almost never applicable	Almost always applicable	Applicable in specific situations	Almost never applicable
Sizing of operating reserves			Almost always applicable	Applicable in specific situations	Almost always applicable	Almost never applicable	Almost never applicable
Generation scheduling			Almost always applicable	Almost always applicable	Almost always applicable	Applicable in specific situations	Almost never applicable
Network studies	Static	Load flow	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable
Network studies	Static	Static security assessment	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable	Applicable in specific situations
Network studies	Static	Short-circuit currents	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable
Network studies	Dynamic	System stability	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable	Applicable in specific situations
Network studies	Special	Grid connection	Almost always applicable	Almost never applicable	Almost always applicable	Almost always applicable	Applicable in specific situations
Network studies	Special	Defence plans	Almost always applicable	Almost never applicable	Almost always applicable	Almost always applicable	Applicable in specific situations (UFLS & UVLS)

Legend: **Almost always applicable** | **Applicable in specific situations** | **Almost never applicable**

Table ES3: Technical studies and how they address key VRE integration challenges

		Technical study	Integration challenge: Generation adequacy	Intraday flexibility	Stability	Static thermal/ voltage grid limits	Short circuits and protections	Power quality
		Generation adequacy	■					
		Sizing of operating reserves		□	■			
		Generation scheduling		■				
Network studies	Static	Load flow				■		
Network studies	Static	Static security assessment				■		
Network studies	Static	Short-circuit currents					■	
Network studies	Dynamic	System stability			■			
Network studies	Special	Grid connection			■	■	■	■
Network studies	Special	Defence plans			■	■		

Legend:

■	□	(blank)
Almost always applicable	**Applicable in specific situations**	**Almost never applicable**

Target level for penetration of variable renewable energy

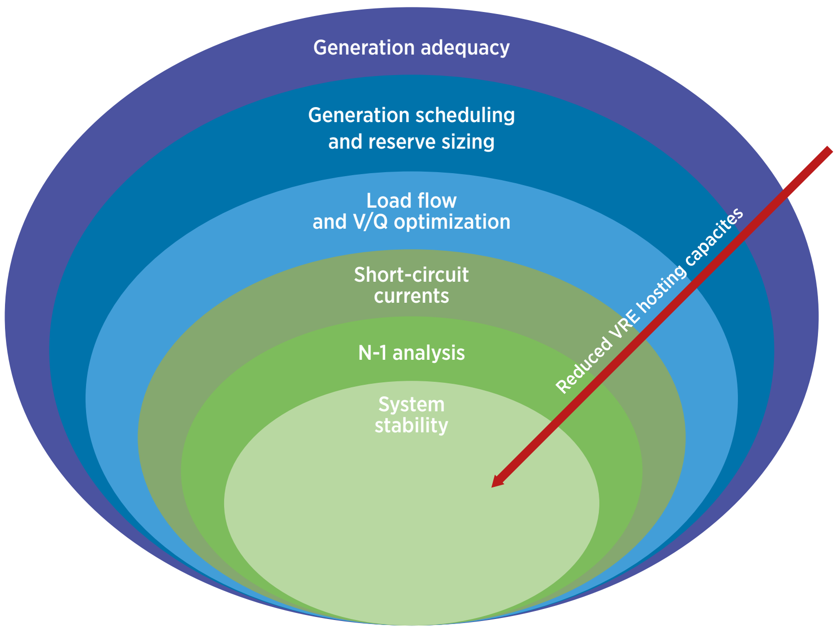
When selecting the technical studies to plan for the integration of VRE in a given small-island power system, one first has to consider the targeted or expected level of VRE penetration at the system level. Three qualitative levels of maximum instantaneous VRE penetration (compared to the load) are considered – low, medium and high – following the same approximate ranges as in IRENA (2013).

If at any point in time the share of **VRE generation stays below 10–15 %** of the total instantaneous load, the VRE penetration can be described as low and no significant integration issues are expected. However, this **does not mean that no study is required**, since dedicated grid connection studies for each of the planned VRE projects remain necessary. These studies are carried out during the development phase of new generation assets by the project developer (whether the utility itself or a private stakeholder).

For **medium and high levels** of VRE penetration, a **different set of technical studies** must be carried out. In these cases, the analysis should start with studies at the system level, considering only load-generation balance needs. This includes studies of *generation adequacy, operational reserve sizing, generation scheduling* and *frequency stability*. If frequency instabilities are identified, a *defence plan study* is also recommended to ensure avoiding a system collapse.

Any island with a transmission grid can make use of studies on load flows, static security assessment, short-circuit current study, transient stability, frequency stability and voltage stability. Ensuring that no technical issue would occur in the presence of VRE requires setting a global penetration limit for the grid (before the application of possible mitigation measures) that is equal to the minimum of the hosting capacities found in the different studies. Figure ES2 provides a general example of the different degrees of limitation to VRE integration posed by different studies[4].

Figure ES2: Limitations for VRE integration resulting from different technical studies



* Order may vary depending on the characteristics of the SIDS system

4 In this example, system stability studies would set the maximum VRE hosting capacity of the system.

Solutions to expand variable renewables

Notably, the actual technical limit for the shares of VRE – and therefore the final hosting capacity on a system –will depend on the readiness to invest in developing and implementing appropriate solutions to enable higher participation of VRE sources. SIDS can implement a variety of possible measures to increase the VRE hosting capacity of their power systems and reach targeted integration objectives. The options to solve the issues identified through the different technical studies can be categorised as:

- **Infrastructure investments:**
  - Diversification of VRE installations
  - Flexible generating units
  - Energy storage systems
  - Interconnection with neighbouring systems
  - Distribution automation and smart grid technologies

- **Operational measures:**
  - Demand-response programmes
  - Enhanced generation dispatch and control
  - Enhanced defence plans
  - Automatic power controller and network monitoring
  - Short-term VRE production forecast

- **Technical requirements on VRE generator capabilities:**
  - Grid code requirements for integration of VRE generators.

Given the large choice of possible solutions to address VRE grid integration challenges, selecting the most appropriate ones for a given small island developing state can be a challenge. A recommended approach is to perform an initial qualitative screening of possibly suitable solutions by mapping the identified technical challenges at the targeted VRE penetration level with the ability of the different options to solve these challenges (see Table ES4). Other factors to consider include the practical and logistical applicability of different solutions, their commercial availability, the required capital investments, the timeline for implementation and environmental impact.

Once candidate solutions have been chosen, they should be assessed by means of technical studies to ensure that they will indeed solve the identified violations of performance criteria with targeted VRE shares. When multiple solutions can address the same technical challenges, the final selection should be based on a cost-benefit analysis. Such analysis can be conducted on each individual solution but also on hybrid mixes of solutions.

Just as importantly, 100 % reliability or service quality is nearly impossible to achieve. A **trade-off exists between robustness and cost** in the operation and planning of power systems, with the system's ability to withstand a large range of events adding directly to the costs (for either investments or operation) entailed to achieve high reliability levels. This is especially relevant for power systems in SIDS, given that cost effectiveness is a key challenge for them and considering that small systems typically are more vulnerable to the consequences of outage (or other) events than larger interconnected systems.

Further reading

IRENA (2013), Smart Grids and Renewables: A Guide for Effective Deployment. International Renewable Energy Agency, Abu Dhabi.
www.irena.org/publications/2013/Nov/Smart-Grids-and-Renewables-A-Guide-for-Effective-Deployment

Table ES4: Mapping of technical solutions with addressed challenges and other evaluation criteria

	Solutions	VRE integration challenge addressed						Other evaluation criteria	
		Generation adequacy	Intraday flexibility	Stability	Static thermal/ voltage grid limits	Short circuits and protections	Power quality	Applicability to SIDS	VRE penetration threshold
Infrastructure investments	Diversification of VRE installations	High impact	High impact	High impact	High impact	Moderate impact	Moderate impact	Low-medium	Low
Infrastructure investments	Flexible thermal generation	High impact	High impact	High impact	(Almost) no impact	(Almost) no impact	(Almost) no impact	Low-medium	Medium
Infrastructure investments	Electricity storage	High impact	High impact	High impact	Moderate impact	Moderate impact	High impact	Medium-high	Medium
Infrastructure investments	Conventional transmission and distribution grid reinforcements	(Almost) no impact	(Almost) no impact	High impact	High impact	High impact	High impact	Medium-high	Low
Infrastructure investments	Interconnection with neighbouring system	High impact	High impact	High impact	(Almost) no impact	(Almost) no impact	(Almost) no impact	Low-medium	Medium
Infrastructure investments	Smart transmission	(Almost) no impact	(Almost) no impact	High impact	High impact	(Almost) no impact	Moderate impact	Low	Medium-high
Infrastructure investments	Distribution automation	(Almost) no impact	(Almost) no impact	High impact	High impact	High impact	(Almost) no impact	Low-medium	Medium-high
Operational measures	Demand response	High impact	High impact	High impact	Moderate impact	(Almost) no impact	(Almost) no impact	Medium	Medium-high
Operational measures	Adapted generation dispatch and control	Moderate impact	High impact	High impact	Moderate impact	(Almost) no impact	(Almost) no impact	High	Low-medium
Operational measures	Adapted defence plans	(Almost) no impact	High impact	High impact	High impact	(Almost) no impact	(Almost) no impact	High	Low-medium
Operational measures	Automatic power controller and network monitoring	(Almost) no impact	High impact	High impact	High impact	(Almost) no impact	(Almost) no impact	Medium	Medium
Operational measures	Accurate VRE forecasts	(Almost) no impact	High impact	High impact	Moderate impact	(Almost) no impact	(Almost) no impact	Medium	Medium
Technical requirements for VRE generators		(Almost) no impact	High impact	High impact	High impact	High impact	High impact	Medium-high	Low-high

Legend: High impact | Moderate impact | (Almost) no impact

INTRODUCTION

A large number of **Small Island Developing States (SIDS)** have started to **integrate renewable energy** into their electricity supply mix or are planning to do so in the near future. Due to the particular geographical and socio-economic context of SIDS, various and important benefits will be achieved through this transformation of their power systems. These benefits include, in particular, the potential of **reducing imports of fossil fuels**, which many SIDS currently rely on for electricity generation.

Achieving a transition to renewable energy depends, among other factors, on the **ability of the local power system to integrate renewable energy technologies** while maintaining adequate levels of security and reliability. Such integration intensifies the **technical challenges** that SIDS already face in operating their power systems, especially if high shares of variable renewable energy (VRE) – such as solar photovoltaic (PV) and wind power – are foreseen.

Utilities and energy planners in SIDS will need to carry out **planning studies** to anticipate potential challenges and to identify suitable preventive solutions. Failing to successfully carry out technical planning activities might result in a slower expansion of VRE, in the need to invest in expensive retrofitting of network assets, in lower reliability of the power system and/or in the need to curtail VRE production (impacting investment profitability).

This document aims to help stakeholders in SIDS devise and carry out technical studies to **plan the expansion and the operation** of their power systems. It will assist in **finding suitable technical solutions** to enable the integration of high shares of VRE. The content of the document is applicable for a **large variety of SIDS**, ranging from very small islands with only a few distribution feeders to large islands with more complex transmission networks.

This document is directed primarily towards utility staff members in SIDS but also can benefit other stakeholders, including, for example, development partners, consultants and public authorities in charge of planning the energy sector. Readers are assumed to be familiar with basic technical concepts of power system operation and planning. The overview brochure that accompanies this guide provides a quick glimpse of the high-level recommendations emerging from this guide. Although this document focuses primarily on SIDS, the proposed methodological framework also could be applied, with minor adaptations, to systems planning to integrate significant amounts of VRE in other areas.

This document has been prepared under the **SIDS Lighthouses Initiative led by IRENA**. It complements other publications issued by IRENA on the integration of renewable energy in SIDS (IRENA, 2012, 2015a). The focus of this guide is primarily on **technical issues**, with only minor coverage of economic aspects. Since economics also is of prime importance in the context of SIDS, readers who are interested in the economic evaluation of renewable energy integration in SIDS can refer to previous IRENA publications (such as IRENA, 2015b, 2017a) for more details on the topic.

The main overarching questions addressed in this document are:

- How can utilities or regulators determine the level of VRE that could be accommodated in the existing power system, without major investments, while complying with all operational limits and reliability requirements?

- What are the main technical issues to be investigated, depending on power system characteristics, and what technical studies are needed to find the maximum hosting capacity for VRE in a given system?

- What are the possible ways to increase this hosting capacity in the near and long terms, up to a given VRE target share?

- What mitigation strategies would work to resolve identified technical issues, considering possible infrastructure investments as well as operational measures and technical requirements for VRE-based power generators?

Regarding the second point above, the actual technical limit for the shares of VRE – and therefore the final hosting capacity on a system – will depend on the readiness to invest in developing and implementing appropriate solutions to enable higher participation of VRE sources.

The scope of this guide does not cover the definition of desirable generation expansion scenarios or renewable energy target shares for SIDS; a key reason is because these depend mostly on policy priorities and on economic resources rather than on technical rationales. Such scenarios and targets are used as inputs for the studies described in this guide. IRENA, through the SIDS Lighthouses Initiative, supports its member SIDS in preparing roadmaps for renewable energy integration that include the development of scenarios for the future generation mix; for further information see IRENA (2017a). In addition, readers can refer to the IRENA report *Addressing Variable Renewable Energy in Long-term Energy Planning (AVRIL)* for best practices in defining long-term scenarios aimed at large-scale VRE integration (IRENA, 2017b).

This document covers the following types of technical studies that are often used to plan the integration of VRE in SIDS power systems:

- **generation adequacy and reserve sizing studies,**
- **generation scheduling studies** (including unit commitment and economic dispatch), and
- **network studies, including static and dynamic network analyses.**

These studies address the various technical challenges of VRE integration through **well-defined methodologies** that can be repeated over time and used in different contexts of VRE integration. Most of the types of studies presented can be applied at both the **long-/mid-term planning stage** (from months to years ahead of real-time operation) and at the **operational planning stage** (from day to week ahead). The purpose of these studies is to support decisions that can be made at these planning stages in order to avoid technical issues in real-time operation or frequent activation of remedial actions (such as load shedding), which could be expensive or detrimental for consumers. The links between the different studies are highlighted in the guide as well as the impact on the final system operation of decisions made at different planning stages.

The various power system studies for VRE integration must not be considered as one-off activities, but rather as **continual and recurrent processes**, with iterative learning, given the **dynamic nature of VRE deployments over time.**

For each technical study covered in this guide, the following main aspects are addressed:

- purpose of the study, as it relates to the technical constraints that might possibly limit VRE integration;
- relevance of the study according to power system characteristics;
- time horizon at which the study should be conducted (from hours ahead to years ahead) and time frame of the physical phenomena represented;
- required input data;
- relevant operational conditions to be represented and criteria for analysis of the results;
- examples of software tools available to perform each study;
- method for assessing how a given technical solution or mitigation strategy (*e.g.,* new or modified infrastructure or operational measure) can increase the potential penetration of VRE.

Although general recommendations are given about power system modelling and simulation, the practical implementation of models using specific simulation software is out of the scope of this document. Because model definitions and user interfaces can vary depending on the chosen simulation tool, hands-on experience and/or specific training is required to proficiently use such software.

This guide is structured so that the chapters are self-contained modules that can be read separately. All chapters, however, are linked as a **logical sequence of steps to follow when planning for the integration of VRE in SIDS**. The document starts with identifying potential challenges related to VRE integration, and the particular influence that SIDS power system characteristics have on these challenges. Then, the sequence of technical planning studies needed to quantify technical constraints on VRE integration is presented. Finally, the suitability of different solutions for increasing the VRE penetration is compared depending on the issues identified.

Chapter 1 presents the general context and challenges of SIDS, as well as the rationale for developing renewable energy sources as part of their energy policies. The technical challenges linked to the integration of VRE in their power systems are introduced.

Chapter 2 discusses how the particular characteristics of a given SIDS power system influence its capability to safely integrate increasing shares of VRE.

Chapter 3 introduces the different technical assessments that are relevant when planning the expansion and operation of SIDS power systems to integrate VRE generators. It explains how the required planning process and studies depend on the particular system characteristics and on the expected challenges of VRE integration.

Chapters 4 to 8 present different types of studies, classified according to the physical phenomena and the system components that are analysed. For each chapter a general description of the studies is given, including a description of the flow of information that is usually followed to conduct such studies. Practical information such as required input data and typical software packages is condensed in summary tables at the end of each description. References for further reading are provided as well.

Chapter 4 explains how to perform a generation adequacy study to ensure that a SIDS' generation expansion plan and the integration of VRE can supply the load with a sufficient level of reliability. It also provides recommendations on how to size the operating reserves, focusing on the need to compensate sudden variations in VRE power output.

Chapter 5 explains how to assess the impact of VRE on the generation dispatch and related needs in terms of flexibility. It details how to carry out generation scheduling studies to ensure that sufficient flexibility is present in the SIDS power system and that the required operating reserves can be supplied.

Chapter 6 focuses on the steady-state network studies to be carried out in order to perform expansion and operational planning of transmission and distribution networks in the presence of VRE. It includes load flow and short-circuit analyses.

Chapter 7 focuses on the network studies to be carried out in order to perform expansion and operational planning of SIDS from the point of view of power system stability.

Chapter 8 focuses on special network studies including defence plan actions and grid connection studies.

Chapter 9 details the solutions that can be applied to solve the issues identified through the different technical studies. It covers infrastructure investments (grid reinforcements, storage assets, smart grids, etc.), operational measures (adapted generation dispatch and control strategies, network monitoring and control, demand response, etc.) and technical requirements on VRE generators' capabilities. The chapter explains how to assess, from a technical perspective, the most suitable options for a particular system in order to solve the anticipated technical issues. It also explains how to integrate the envisioned solutions in the different technical studies to check that they can overcome the identified constraints. Several case studies are used to illustrate the different types of solutions.

1. TRANSFORMING POWER SYSTEMS IN SMALL ISLAND DEVELOPING STATES: OPPORTUNITIES AND TECHNICAL CHALLENGES

This chapter presents the general context of SIDS and the main motivations behind the deployment of renewable energy in their particular environment. It then explains the technical challenges associated with integration of VRE in island power systems. Whereas some technical constraints are identical to the ones faced by larger – and possibly interconnected – systems, specific issues arise due to the unique characteristics of SIDS power systems.

1.1. General context of Small Island Developing States

The United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States currently identifies 57 SIDS (UN-DESA, n. d.).

SIDS face similar economic and environmental challenges, including (UN-OHRLLS, 2011):

- "... narrow resource base depriving them of the benefits of economies of scale
- small domestic markets and heavy dependence on a few external and remote markets
- high costs for energy, infrastructure, transportation, communication and servicing
- long distances from export markets and import resources
- low and irregular international traffic volumes
- little resilience to natural disasters

Figure 1: Map of Small Island Developing States

Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA. The term "country" as used in this material refers, as appropriate, to territories or areas.

- growing populations
- high volatility of economic growth
- limited opportunities for the private sector and a proportionately large reliance of their economies on their public sector
- and fragile natural environments".

These challenges are similar to those faced by other islands or isolated territories, including remote rural and landlocked areas.

Some countries categorised as SIDS are not islands when following a strict geographical definition. This is, for example, the case of low-lying coastal states of Belize, Guyana and Suriname in the Caribbean (see Figure 1). These countries are nonetheless considered as SIDS because they share similar characteristics with the other island countries or territories categorised as such.

1.2. A case for the deployment of renewable energy

A considerable number of SIDS are planning to integrate large shares of renewable energy into their electricity supply mixes. Among the main reasons for this are:

- the currently high costs of producing electricity in SIDS due to the widespread use of diesel generators that run on imported fuels;
- the local availability of renewable energy resources, which, depending on the small island developing state, can include solar, wind, geothermal and hydroelectric resources;
- the environmental and societal benefits of renewable energy use (reductions in greenhouse gas emissions, job creation, strengthening of local communities, etc.);
- Political support for the development of sustainable energy supply strategies, in particular as a means to contribute to international efforts on climate change mitigation, for example through Nationally Determined Contributions (NDCs) defined in the Paris Agreement.

Considering these potential benefits, many SIDS have adopted renewable energy targets, with some SIDS, such as Samoa and the Cook Islands, even aiming to achieve 100 % shares of renewable energy in their electricity mixes in the medium term.

The present document is intended to provide guidelines for the planning of small-island power systems; these could be followed for any particular target for renewable energy integration set in a small island developing state, from low to high shares.

1.3. Basic principles of power system operation and planning

The basic principle for power system operation and planning is to deliver electricity to the final consumer at least cost while meeting pre-defined criteria in terms of reliability and quality of service. The following paragraphs discuss this principle to facilitate understanding of the technical challenges related to VRE integration.

The first main requirement for power system operation and planning is to ensure sufficient generation capacity to supply the electricity demand and adequate transmission and distribution networks to transfer the generated power to final consumers with minimal losses.

Contrary to other types of commodities, electricity is still difficult to store on a large scale, which implies that the power produced should at all times match the power consumed in the system. Any imbalance between production and consumption is reflected by a change in the system frequency.

Devices that consume electricity can only operate properly within specific frequency and voltage ranges. The power system operation must therefore ensure that electricity is supplied within these ranges.

To achieve this, it is not sufficient to simply ensure that enough active and reactive power can be produced and transmitted to final consumers; utilities (or market players) must provide additional services as well. These include the following two main types of services:

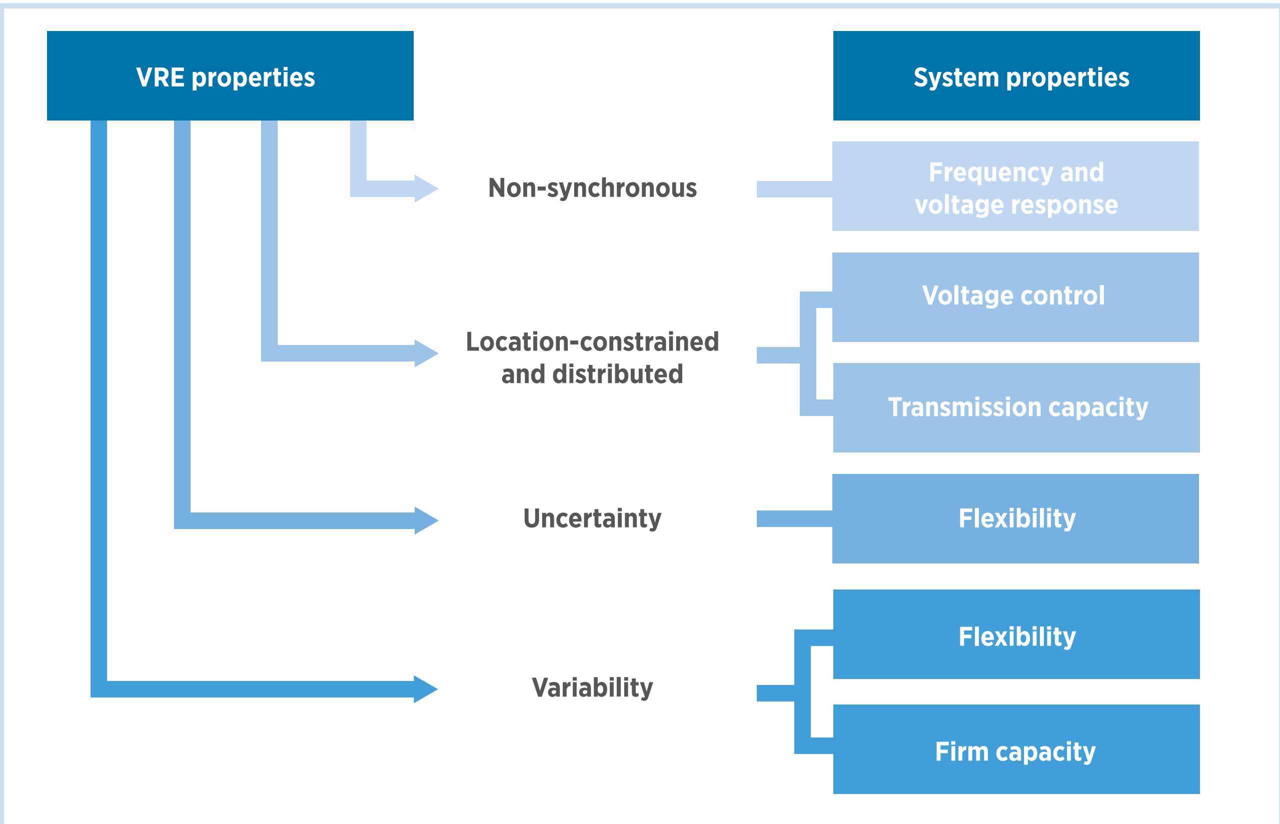
- ***Frequency control***, which activates the available resources to compensate for any imbalance between load and generation. These imbalances are due to uncertainty or variability on the supply or demand side. They can, for example, be due to sudden events such as the outage of a generator or of a power line. Shedding consumer loads to maintain the balance is usually the last-resort option for frequency control.

- ***Voltage control***, which ensures that the voltage is maintained within adequate bounds in all parts of the system. It is performed by the production or absorption of reactive power by generation units and/or by changing the settings of some network equipment such as reactor banks, capacitor banks, transformer taps, etc.

Achieving 100% reliability or quality of service in a power system is nearly impossible. Even the most robust power systems can be subject to very rare outage events (such as the simultaneous loss of multiple generators or power lines) that they are not able to fully withstand. Frequency and voltage could experience very large deviations or even a full collapse. In some specific conditions, controlled load shedding may need to be applied to ensure system stability, temporarily preventing some customers from having access to electricity.

A trade-off exists in the operation and planning of power systems between the robustness to withstand a large range of events, and the costs (either for investments or for operation) that are needed to achieve high reliability levels. This trade-off is especially critical in SIDS, given that small power systems are typically more vulnerable than larger interconnected systems to the consequences of outage (or other) events and because cost effectiveness is a key challenge in SIDS.

Figure 2: Key links between variable renewable energy, power system properties and planning



1.4. Technical challenges of integrating variable renewable energy

Historically, power systems in SIDS have been based mostly on conventional generation such as diesel and hydropower. Together with the network infrastructure, conventional generators provided all of the services required to operate the system at given reliability and power quality levels. Because VRE has different technical characteristics than conventional generators, new challenges can arise when it is integrated into the electricity supply mix.

VRE technologies refer to electricity generators that have variable power output that depends on the availability of the underlying primary renewable energy source. Solar PV and wind power are the main technologies that are traditionally considered to be VRE.

Because the output of VRE generators is difficult to control (except for curtailment actions) and difficult to predict with high accuracy, these generators are more challenging to integrate into power systems than other types of technologies, such as conventional fossil-fuelled generators or dispatchable renewable energy generators (*e.g.* biomass, geothermal and reservoir hydropower).

Figure 2 synthesises the main properties that differentiate VRE from conventional generation and relates them to specific properties of the power system that might be impacted by these differences.

The main VRE properties that can have an impact on the power system are:

- ***Non-synchronous*** nature when interfaced with the grid through power electronics devices, which decouple their power source from the frequency and voltage of the system and therefore leads to different dynamic response to network events. For example, VRE generators do not provide the same inertial response or short-circuit currents as conventional generators based on synchronous machines.

- ***Location,*** which can be constrained by the availability of renewable energy resources and might require significant network extensions or lead to network congestions. The modularity of VRE technologies also means that they can be deployed at very small scales in distribution grids, which historically were not designed to accommodate power generation.

- ***Uncertainty*** related to their generation, or the unexpected change in their power output compared to forecasted values.

- ***Variability,*** which is the expected change in power output due to variability in the available primary resource (solar irradiation or wind speed) occurring over time.

The following sections map the aforementioned properties with potential technical challenges that may arise when integrating high shares of VRE in island power systems. Significantly, these challenges are driven not only by the characteristics of VRE technologies, but by the characteristics of the power system under consideration (load profile, existing network and generation infrastructures, etc.), as explained in Chapter 2 of this guide.

Ensuring sufficient firm capacity for generation adequacy

The first challenge linked to VRE integration is the need to ensure that, despite the variability and the uncertainty, the generation fleet will still be able to reliably supply the electrical load at all times. This capability is referred to as **generation adequacy**.

The firm capacity of a generator reflects its contribution to generation adequacy. It can be defined as the amount of power generation that can be guaranteed to meet demand at any given time, even under adverse conditions (EIA, n.d.).

Because VRE generation capacities are dependent on natural variable primary resources, the availability of VRE capacities cannot be ensured with the same confidence level as for dispatchable generators (such as thermal generators or hydropower with reservoir). There is no guarantee that VRE generation profiles will match temporally with the demand profile. Therefore, the fraction of VRE installed capacity that can be considered as firm capacity is typically lower than for dispatchable generators.

Thus, generation adequacy levels can potentially deteriorate when VRE generators alone are used to cover load growth or to replace dispatchable capacities.

Generation adequacy can be assessed at the long-/mid-term planning stage[3] (from months to years ahead of real-time operation) through probabilistic metrics such as the loss of load expectation (LOLE) or the expected energy not served (EENS). Target values of these metrics are often used when planning for the installation of future generation capacities (*e.g.,* maximum 24 hours LOLE per year). The specific studies required for evaluating whether such criteria are met in the presence of VRE are discussed in Section 4.1.

Addressing flexibility needs due to variability and uncertainty

This challenge is linked to the need to accommodate intraday variations, from minutes to hours, in the net load (the load to be served by conventional generation or energy storage devices) with the generation system.

While adequacy focuses on the availability of sufficient generation capacity, the flexibility challenge relates to modulating (or ramping) the power supply from one time period to the next, inside a given day, to match the demand. Flexibility is related to the need to compensate for any deviation between forecasted load or generation levels and the actual levels observed in real time.

The intraday fluctuations of VRE power outputs impact the net load (or residual load) to be supplied by the dispatchable generators or other supply means in the system (*e.g.,* storage). Depending on the operational constraints and ramping capabilities of these assets, a risk exists of not being able to maintain the balance between load and generation in case of a large and/or sudden increase or decrease in the net load. A higher occurrence of start-up/shutdown cycles of conventional generators also can be expected, which can lead to higher maintenance needs or shorter lifetimes for certain assets.

Even when the dispatchable generators have the technical capability to accommodate sharp variations in net load, the operational practices of SIDS might not make it possible to leverage the full flexibility potential of these generators. This can, for example, be the case if there is no operational planning practice in place to regularly update the generation schedule for the different plants, or if only limited operating reserves are kept.

In small-island power systems, simultaneous short-term variations in the output from multiple VRE generators are more likely to be correlated than in larger systems, since the weather conditions are generally similar in different parts of the island. VRE integration strategies based on several VRE technologies (*e.g.,* wind and solar) and on projects spread over multiple geographical locations are typically less exposed to these issues.

In addition to the impacts resulting from VRE variability, the uncertainty related to VRE generation introduces further flexibility challenges for the system. The day-ahead or intraday forecast of VRE power outputs typically includes errors that must be compensated for by adapting the dispatch of other generators (or the activation of other flexibility means such as energy storage) present in the system. In the short term (*e.g.,* intra-hour) such compensations are performed through the available operating reserves.

The sizing of operating reserves is discussed in more detail in the second part of Section 4.2. Generation scheduling (unit commitment and economic dispatch) in the presence of VRE, which is also related to the flexibility challenge, is addressed in Chapter 5.

Ensuring system stability

Power system stability is "the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected

3 The reason for assessing adequacy only in long-/mid-term planning stages is that the solutions of adequacy problems usually require investments in new generating units or energy storage devices, which take considerable time to be deployed.

to a physical disturbance, with most system variables bounded so that practically the entire system remains intact" (Kundur et al., 2004).

In other words, a stable system is robust enough to maintain voltage and frequency within acceptable limits after being subject to small disturbances such as natural variations in the system load or to large disturbances such as a short circuit or the loss of an important generating unit.

System stability is among the main technical concerns when targeting high shares of VRE in small power systems. Since the electro-mechanical characteristics of the system often change significantly with high penetration levels of VRE, the response of the system to disturbances also changes, and this may affect its stability.

Power system stability is typically described according to three types of physical phenomena:

- ***Frequency stability*** is the ability of the power system to maintain the frequency within an acceptable range after a disturbance resulting in a load and generation imbalance. In small islands this is the major stability concern due to the limited size of power systems and the consequent small system inertia, which makes the frequency more sensitive to any imbalance.

  Large-scale VRE integration may pose new challenges to keeping frequency stable and within acceptable ranges after disturbances. VRE is usually connected to the network through power electronics-based interfaces (*i. e.,* inverters), which do not intrinsically provide inertial response, contrary to conventional synchronous generators. In addition, these sources have a limited contribution to operating reserves due to the lack of controllability of the primary energy source.

  In recent years, efforts have been made to develop advanced VRE power plant design and control schemes in order to provide VRE with synthetic inertia and frequency control capabilities. While downward frequency control, through reduction of active power during over-frequency, is now becoming a standard capability for VRE, synthetic inertia and upward frequency control are still rarely implemented in VRE projects. This is because they require more complex technical solutions and they often imply a reduction in the total energy that can effectively be injected into the grid.

- ***Rotor angle stability*** refers to the ability of synchronous machines of an interconnected power system to remain in synchronism under normal operating conditions and after being subjected to a disturbance (Leelaruji and Bollen, 2015). It comprises transient stability and small-signal stability:

  Transient stability is related to the ability of the generators in the system to remain in synchronism (rotating at the same electrical speed) after the occurrence of a fault.

  Small-signal stability concerns poorly damped electromechanical oscillations and interactions between equipment control loops that might result from the physical interaction between the different elements of the power system, including the VRE generators. Small-signal stability problems are unlikely to occur in the majority of small-island electrical systems due to the short electrical distances of the networks and to the characteristics of the generation fleet.

  Rotor angle stability can be impacted by the widespread deployment of VRE sources due to the reduced equivalent system inertia and more constrained voltage control means.

- ***Voltage stability*** is the ability of a power system to maintain the voltages within an acceptable range at all buses in the system after being subjected to a disturbance. The integration of VRE can lead to dynamic voltage stability issues and to possible voltage collapses in instances where reactive/voltage control is not provided by VRE generators, if their integration significantly changes the spatial distribution of reactive power sources in the network or if they are not able to sustain temporary under- or over-voltage conditions. Although usually analysed separately, voltage stability issues also can lead to rotor angle or frequency instabilities if no corrective actions are taken. All types of stability problems need to be studied if possible.

Compliance with the physical limitations of the network

Integrating a large amount of VRE (or any other power plant type) in a given portion of the network at the transmission or distribution level can lead to power flows for which the system was not initially designed. This creates a risk of exceeding the thermal capacity, *i. e.,* overloading, of network elements (*e. g.,* lines, cables and transformers) either in normal operating conditions or following an outage, when some network elements become unavailable.

The integration of VRE at locations close to final consumers can reduce power flows through the network and therefore decrease network losses. The power levels and temporal generation profiles of VRE must, however, match those of the local demand in order to have such an effect (in other words, the coincidence factor between local VRE production and the load must be high).

If proper planning is not executed, the integration of large amounts of VRE can lead not only to overloading of the existing network elements, but also to voltage control problems and therefore to potential violations of voltage limits (over- or under-voltage), which can potentially lead to malfunctioning of or damage to the appliances of end-users.

In the case of distributed renewable generators connected to low-voltage grids (such as rooftop solar PV), phase unbalance issues also are possible if proper considerations are not taken into account.

Ensuring effective functioning of protection systems

VRE that is connected to the grid through power electronics-based interfaces has limited short-circuit currents when compared to conventional power plants equipped with synchronous generators.

High penetration of VRE therefore may lead to reduced short-circuit currents. Given that protection systems are generally set and co-ordinated to isolate faults for high short-circuit currents, there is a risk that they might not properly operate under a massive presence of VRE.

In distribution networks, the presence of VRE can lead to power flows in the opposite direction than initially planned (from sub-stations to consumers). These reverse flows happen when local generation is higher than local consumption in a part of the network. Such conditions may lead to malfunctioning of protection systems in the event of a fault and to unnecessary disconnections of healthy parts of the network, as well as to activation of reverse power flow protection devices.

Maintaining power quality within acceptable limits

In certain conditions, the integration of power electronics-based VRE sources (*e. g.,* solar PV) can lead to power quality issues due to the particular characteristics of these devices. Voltage and current signals might deviate from ideal sine waves due to the presence of high harmonics contents generated by power electronics. Flickers or sags and swells in the voltage signal could become a major concern when integrating distributed VRE in low-voltage distribution feeders and could negatively impact the operation of end-user appliances.

1.5. Planning the integration of variable renewable energy to overcome technical challenges

Ensuring proper operation of the power system with the integration of VRE requires planning. The planning process normally is based on specific technical and economic studies using modelling and decision-support tools. This guide focuses on the technical component of the planning studies.

Power system planning by means of specific studies is a well-established good practice to enable electric utilities in large systems to anticipate future technical challenges, even when no VRE sources are present or foreseen. The presence of VRE might, however, significantly change the outcomes of these studies as well as the periodicity at which they should be carried out to ensure reliable and cost-effective operation of the power system.

The use of detailed technical studies to support power system planning is not a common practice in many small-island states due mainly to the simplicity of their power systems. Given the wide range of technical challenges that can arise with VRE integration, however, SIDS need to implement a formal planning process to identify, understand and quantify the issues that are most relevant for their power system and for their planned VRE deployment strategy.

Box 1: PLANNING RELIABLE AND EFFICIENT POWER SYSTEMS WITH HIGH SHARES OF VRE IN SIDS

As explained in Section 1.3, a trade-off exists between system reliability and costs when planning the evolution of a power system. When considering VRE integration, the target VRE share can be seen as a third dimension to this planning trade-off. Different strategies can be followed for long-term planning of the power system, depending on the objectives that one wants to achieve regarding these three dimensions. Some of the most common approaches are broadly described below:

1. Set a targeted reliability level for the system and a target share of VRE in the energy mix (or even the planned VRE roll-out) and minimise the total future costs of the system to achieve these levels.
2. Set a targeted reliability level for the system and the allowed total cost of evolution of the system and maximise the share of VRE. If the allowed costs are set to zero, this consists in finding the maximum amount of VRE that can be integrated into the existing system (*i. e.,* the hosting capacity).
3. Set a targeted reliability level for the system and optimise both the VRE deployment strategy and the other system evolutions in order to minimise total costs.
4. Set a targeted reliability level for the system and apply a multi-criteria evaluation to find a suitable trade-off between VRE share and total system costs.

It is generally taken as a constraint that the reliability of the system after integrating VRE should at least be the same as the reliability before this integration. The prevailing planning or operational criteria (*e. g.*, loss of load probability, N-1 criterion, allowed voltage ranges, etc.) are therefore generally not relaxed to allow more VRE in the system. More details on these criteria and how they are applied in the different technical studies can be found in Chapters 4 and 5.

In general, it is extremely difficult to consider the whole variety of power system phenomena (and related VRE technical challenges) in a single optimisation problem or study. A near-optimal solution can be found instead through a series of separate technical studies, each addressing different types of issues. Sometimes, the optimisation process is simplified to the evaluation and comparison of pre-defined scenarios of VRE deployment and other power system evolutions.

In all cases, establishing strong connections and feedback loops between the different technical studies is of prime importance, as illustrated in Chapter 3. The case study on Antigua presented in Box 2 shows how some of the strategies described above were applied in a technical planning study done for a small island developing state.

The technical planning studies are normally based on the representation of the different physical phenomena that occur in the power system, using simulation models. This involves using simulation tools that model the system in detail with all available data and conducting repeated studies to cover a majority of the possible system operating conditions. This allows for a better understanding of the expected impact that any change in the system can have on its behaviour and makes it possible to detect potential technical constraints.

Technical planning studies help in making informed decisions at planning stages to solve the identified technical challenges. Box 1 discusses the commonly followed planning strategies for SIDS power systems with high shares of renewable energy, and Box 2 presents the planning studies conducted in the case of Antigua, where the integration and impact of high penetration of renewable power was considered. (IRENA, 2015c)

Power system technical planning is usually divided (according to the time horizons covered and type of decisions that it supports) in:

- ***Expansion planning (long-/mid-term):*** Power system expansion planning deals with mid- and long-term horizons, aimed at determining the future expansion investment, at least possible cost, required in the power system to supply the forecasted demand while complying with techno-economic and environmental constraints. (IAEA, 1984).

  Specific system studies also are performed at the mid-term planning phase, aimed at defining the technical requirements to be imposed by the grid code for the connection of load and generating units. If a grid code already exists, every time a significant change in the system occurs, the grid code has to be updated to reflect the new behaviour of the system (with special attention given to avoiding regulatory instability).

- ***Operational planning (short-term):*** The main task of operational planning is to determine the optimal generation schedule for the upcoming operation period. In complex power systems, network studies (load flow, stability, etc.) are needed at this stage to assess if the planned generation schedule can meet the forecasted load without violating the technical limits of the equipment and without endangering system stability and security. Deployment of new equipment is not possible at this stage due to the short-term nature of this planning process. In this case, the only available means to set up the system operation are the control variables of the generating units (active and reactive power), transformers (tap position), reactor and capacitor banks (taps) and network topology (network switching).

Power system operational planning in large power systems is usually carried out one or more days in advance of the real-time operation[4], with hourly or even sub-hourly discretisation. However, in small-island power systems, this process could be carried out only when significant changes to the system happen (*i. e.,* commissioning of new equipment, generating unit out of service for maintenance, exceptional climate conditions leading to uncommon load pattern, etc.).

4 Specific simulations could also be carried out in real time (*e. g.*, energy management system).

Box 2: PLANNING VRE INTEGRATION – ANTIGUA CASE STUDY (ANTIGUA AND BARBUDA)

With a population of around 83,000, Antigua is the main island in the country of Antigua and Barbuda, located in the eastern Caribbean. By 2014 the power supply in Antigua relied entirely on diesel generation. The total installed capacity was around 110 megawatts (MW), supplying an annual demand close to 350 gigawatt-hours (GWh) with a peak load of 56 MW. To reduce the dependency on imported fuels, the government and the power utility, Antigua Public Utility Authority (APUA), were considering different options to diversify the generation mix. The options included 18 MW of wind power and 9 MW of solar PV; however, there was no clear understanding and consensus among local stakeholders about the impact that this new type of generation would have on reliable operation of the power system. To solve this issue the government of Antigua and Barbuda, APUA and IRENA did a technical planning study assessing the impact of integration into the grid of the VRE projects included in the expansion portfolio. Four scenarios, summarised in the table below, were set for this assessment. Given the high potential for developing solar PV in the island, an additional analysis estimating the hosting capacity for PV in the current system, without major upgrades, was conducted.

Scenario	Baseline	PV	Wind	PV + Wind
Distributed PV [MW]	0	2	0	2
Centralised [MW]	0	7	0	7
Wind [MW]	0	0	18	18
Total VRE [MW]	0	9	18	27

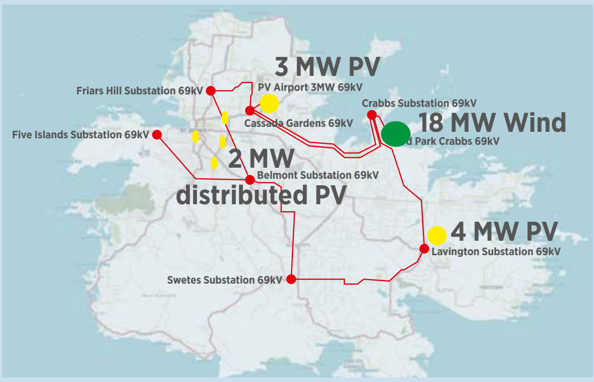
Source: IRENA, 2015c, unpublished.

A simulation model of the power system in Antigua was implemented, using the software PowerFactory, to support the assessments. The conducted analyses followed the procedures described in Chapters 3 to 9 of this guide. Generation adequacy assessments as well as steady-state and dynamic network studies were performed.

The results of the study showed that the integration of PV and wind power generation according to the possible expansion pathways (9 MW of solar PV and 18 MW of wind) was feasible from a technical perspective, provided that several mitigation measures, which do not require major investments or upgrades, were implemented. According to the results of the study a VRE share of 16% of total annual generation could be reached in the scenario with 9 MW of solar PV and 18 MW of wind, with negligible levels of curtailment.

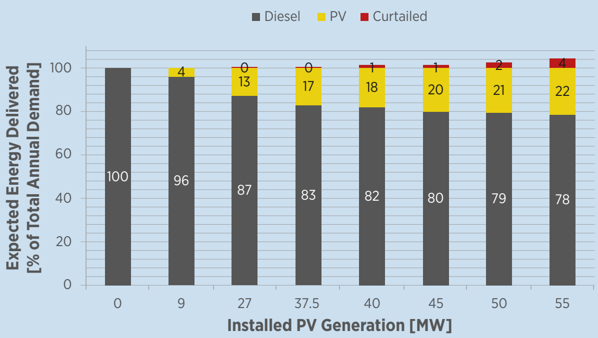
Another relevant output of the study was related to the hosting capacity of today's system: 37.5 MW of solar PV, covering around 17% of the current annual electricity demand, could be integrated with levels of curtailment below 2% without violating the established reliability criteria or the need for major system upgrades.

The assessment showed that going beyond 37.5 MW of installed PV generation, without any storage or demand-side management measure, would result in increasing levels of curtailment due to system reliability constraints (see plot to the right). Thus, without system upgrades no considerable increase in annual energy share would be achieved by increasing the installed solar PV capacity beyond this point. For further information on this study, contact IRENA's islands team (islands@irena.org).



Source: IRENA, 2015c, unpublished.

Boundaries shown do not imply an official endorsement or acceptance by IRENA.



Source: IRENA, 2015c, unpublished.

Technical planning studies and the content of this guide

The technical studies described in the following chapters of this guide focus on quantification of the impact of the integration of VRE, according to the challenges described in Section 1.4, and the identification of appropriate enabling solutions. The described studies are applicable for the time horizons covering expansion planning and operational planning.

The content of the guide does not cover the definition of desirable generation expansion scenarios or renewable energy roadmaps for SIDS; a key reason is that these depend mostly on political priorities and on economic resources rather than on technical rationales. However, establishing such roadmaps is an essential first step in the journey to reach high VRE integration levels, as illustrated in Figure 3.

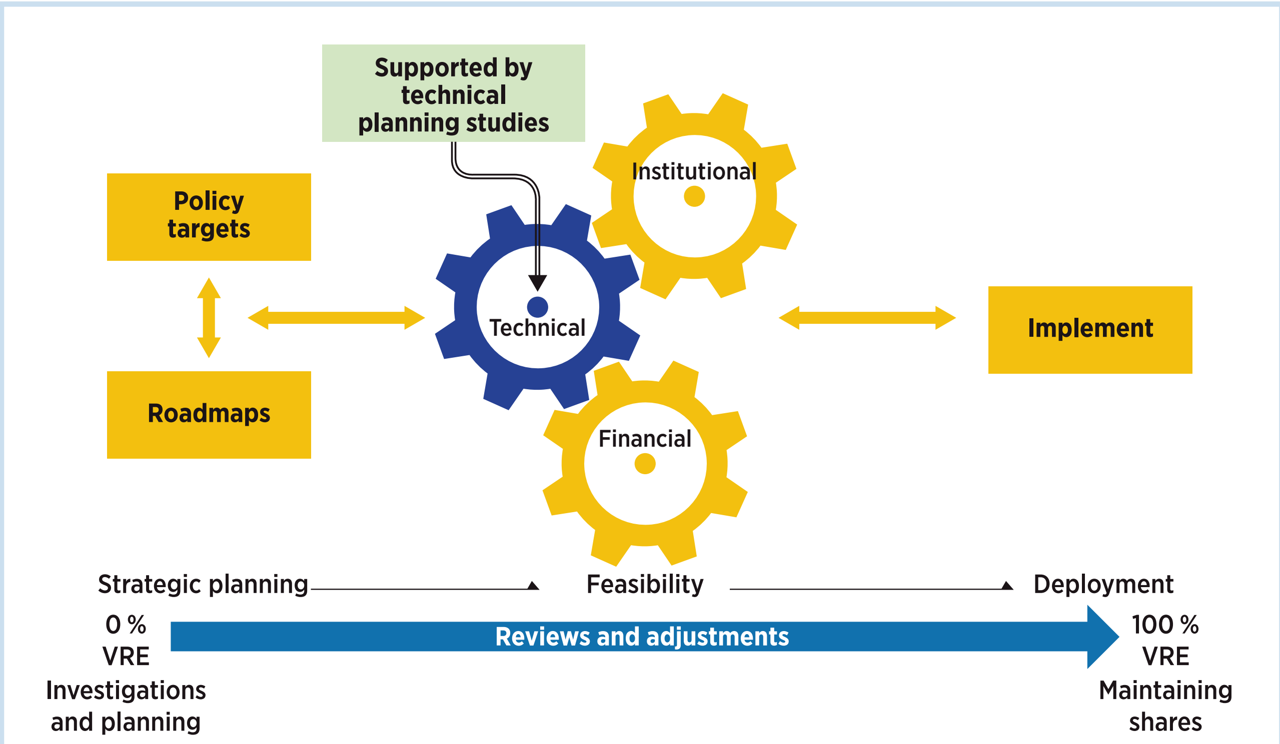
The roadmaps provide the main inputs for the technical studies covered in this guide. Depending on the outcomes of the technical studies, some adaptations to the roadmaps could be recommended, as an iterative process. This guide therefore has strong synergies with the work conducted by IRENA on Renewable Energy Roadmaps for Islands (IRENA, 2017a).

Technical planning studies are the basis for establishing an adequate technical framework, which is one of the pillars, along with financial and institutional frameworks, for the successful deployment of large shares of renewable energy resources in a power system (see Figure 3).

Figure 4 presents an overview of the technical planning methodology proposed in this guide to support the deployment of VRE sources in small-island power systems. Each individual box depicted in this figure is explained in detail in different chapters of the guide.

The planning process starts with a preliminary analysis of the characteristics of the considered SIDS power system (Chapter 2) and how they relate to the technical challenges associated with VRE integration.

Figure 3: The role of technical planning studies in the transformation of the power systems in SIDS

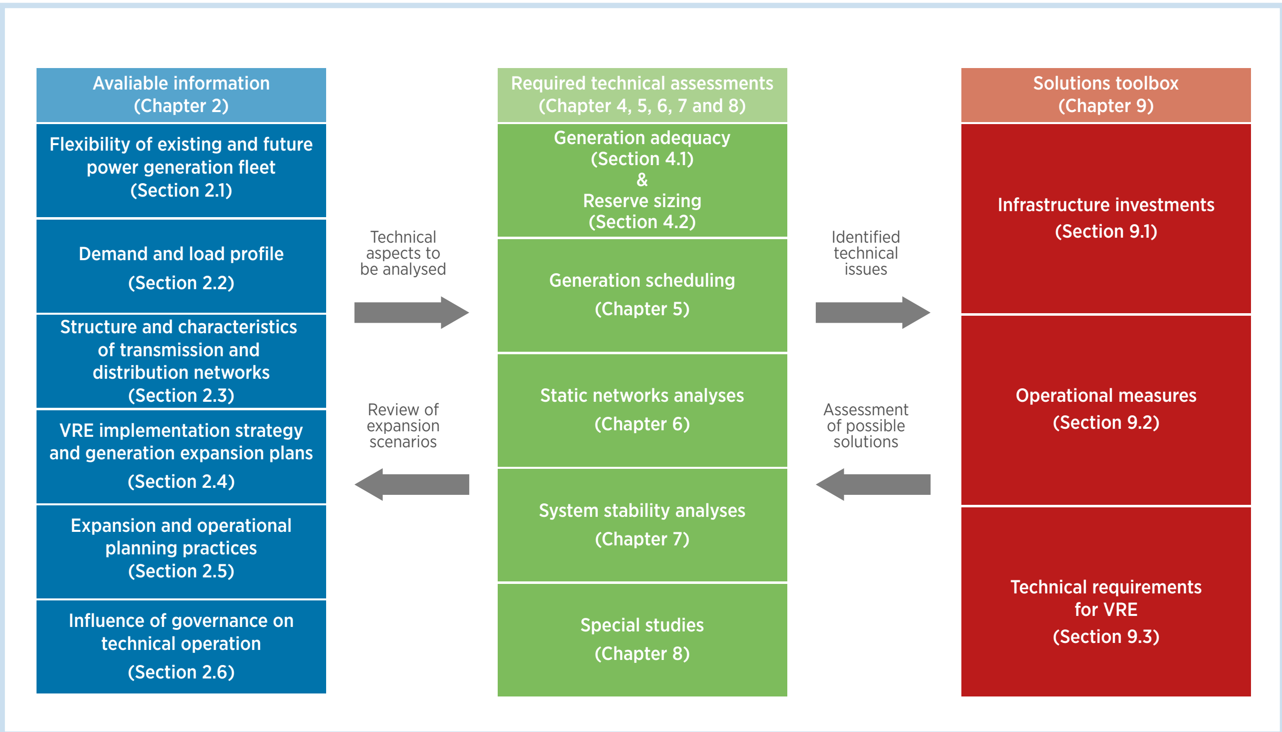


Chapter 3 explains the logical sequence of technical studies that would be required to ensure successful VRE integration that is compliant with all planning and operational criteria. It also explains how the studies can be used during expansion planning (long-/mid-term) and during operational planning (short-term).

Chapters 4 to 8 provide a comprehensive description of the technical studies needed, along with guidelines on how to perform them.

Chapter 9 discusses the adequacy of the different types of solutions that can be used to overcome the issues identified via the technical studies. It also discusses the integration of the identified solutions in the technical studies as a feedback loop to check their effectiveness.

Figure 4: The process for using technical studies to support the integration of VRE in SIDS



2. UNDERSTANDING POWER SYSTEM CHARACTERISTICS AND THEIR EFFECTS ON VARIABLE RENEWABLE ENERGY INTEGRATION

The first step when conducting technical studies to plan for the integration of VRE in a small island developing state is to acquire a good understanding of the characteristics of the power system being studied and of the electricity sector of the island more generally. This is necessary for understanding which technical challenges would have the highest impact in the context of the assessed island and to determine the best approach for using the technical studies in the planning process.

A good understanding of the characteristics of the power system and of the electricity sector is also necessary to define the most appropriate scenarios and operational conditions that will have to be evaluated in the technical studies. If technical issues are detected within the studies, a clear understanding of the system characteristics also will be critical to identifying the most suitable solutions.

This chapter describes the main characteristics of SIDS power systems that are essential when planning the integration of VRE. Six main topics are addressed:

- the flexibility of existing and future power generation fleets
- the demand and load profile
- the structure and characteristics of transmission and distribution networks
- the implementation strategy for VRE and generation expansion plans
- the operational and planning practices of the utility
- the influence of governance of the electricity sector on the technical operations.

Each of these aspects can make the system more or less sensitive to the integration of VRE and either robust or vulnerable to technical issues. The different parts of this chapter detail how these characteristics should be taken into account when planning (from a technical perspective) an island power system for the integration of VRE. The last part of this chapter (Section 2.7) synthesises how these particular characteristics of a small-island power system are linked to the VRE integration challenges described in Chapter 1.

The first three topics listed above focus on physical characteristics of the system and their direct influence on the technical assessments. The last three topics focus on institutional aspects and strategic decisions that affect the physical system and its operation, thus having an influence on the planning studies. Given that this guide is oriented mainly towards technical aspects, the last topic does not cover the whole complexity of institutional matters surrounding the integration of VRE.

While discussing the above characteristics, the different sections of this chapter highlight the fact that all of the power systems in SIDS have their own specificities and requirements and should be treated as particular cases when planning the integration of VRE.

To conduct the different technical studies, the characteristics described in this chapter would need to be detailed in the form of technical data, to be used as inputs to models and simulation tools. Chapters 4 to 8 list the technical data required for each of the described technical studies. A good understanding of the main characteristics of the system is very important when collecting the data necessary for the different studies. Moreover, since data availability can often be a critical issue in SIDS (see Box 4 in Section 3.5), power system planning engineers must have a good understanding of the overall system in order to make suitable assumptions in case of missing information.

2.1. Flexibility of existing and future power generation fleet

The flexibility of a generation system refers to its capability to increase production when demand increases and to decrease production when demand decreases.

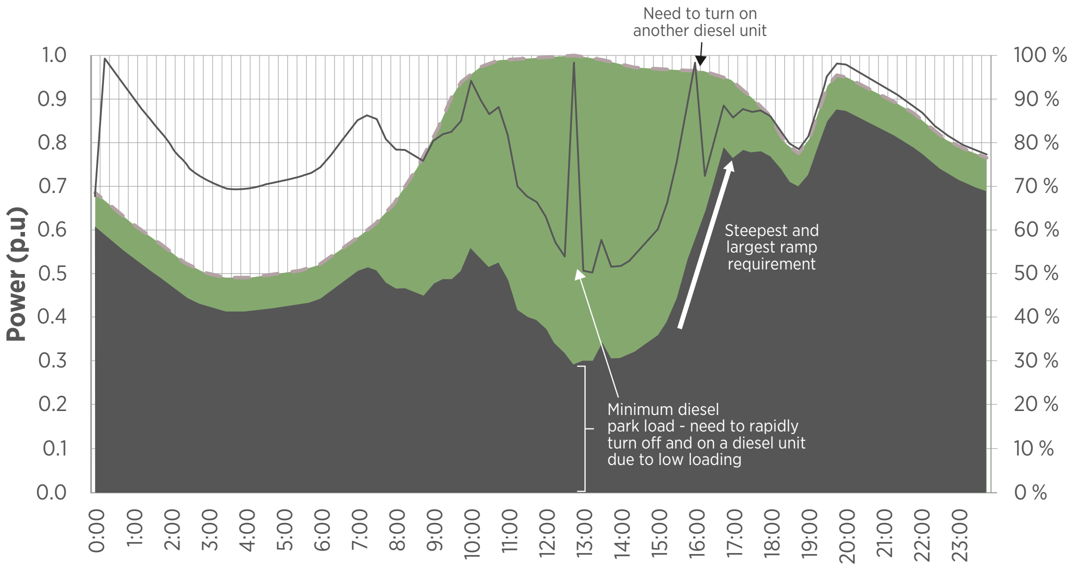
A given generation fleet can be considered to be flexible "if it can respond rapidly to large fluctuations in active power demand and generation" (IEA, 2008). Data show that such fluctuations are due mostly to predictable variations in demand or to unforeseen events such as the outage of a generator or the loss of some loads due to a network fault. With the integration of VRE, additional fluctuations are introduced on the generation side due to the variability of VRE production. The uncertainty in VRE power output also typically leads to higher deviation of final production levels compared to forecasted or expected levels.

Since the power output of VRE generators is typically not controlled, flexibility is generally associated with the conventional generators in the system, which are able to ramp their power outputs in order to follow the variations[5] in net load (*i. e.,* demand minus VRE generation). In case of lack of flexibility in a system, there is a need to recourse to generation curtailment (mainly VRE curtailment) or load shedding in order to restore load and generation balance.

Conventional generators are considered to be flexible when they can:

- rapidly ramp up or down their power generation over time (either automatically, as part of a load-frequency control scheme, or after receiving specific dispatch instructions from operators)
- operate them at part load (*i. e.,* at a low power output compared to their maximum capacity)
- start them up or shut them down rapidly and frequently, without having to wait too much between start/stop cycles.

Figure 5: Representative illustration of net load variability and ramping needs induced by VRE



Based on IRENA, 2015d, unpublished.

5 Storage and demand-response capacities can also contribute to the flexibility when present in the system.

Figure 5 illustrates in a simple way how VRE integration can increase the ramping needs of conventional generators within a day. It shows how the addition of solar PV generation in the system could lead to strong ramping needs during the sunset period in order to compensate for the decrease in solar power. The figure also shows how load for the average diesel generator varies during a day, requiring operation at part load as well as start-ups and stops of units in short periods of time.

Most island power systems rely on diesel generators for their electricity supply. These types of generators are generally flexible, with high ramping capabilities, short start-up/shutdown times and low technical minimum (allowing them to operate at part load). However, there might exist some technical and economic challenges to operate them in a flexible manner with high and frequent variations of their power output, as explained in Box 3.

Besides diesel generators, many other generation technologies can be found in the generation mix of SIDS power systems, with different flexibility characteristics:

- Some larger islands (such as Cuba, Puerto Rico and the Dominican Republic) can have other types of fossil-fuelled generators, such as coal- or gas-fired power plants. Existing coal power plants are relatively

Box 3: IMPACTS OF OPERATING DIESEL GENERATORS TO PROVIDE HIGH FLEXIBILITY

Diesel generators are the most common technology used in SIDS for power generation. Although they are traditionally considered to be the most flexible thermal generators, subjecting them to frequent cycling or operation at part load can have undesirable effects.

The capabilities of a diesel generator depend on several factors, including its design, its age, its operation and maintenance history, and the fuel that it uses. For this reason, it is difficult to provide an exhaustive assessment on how diesel generators are impacted when they are operated to deliver a high level of flexibility. The following list, however, provides a generic overview of the impacts that are reported most often in the literature (see, *e. g.*, Saengprajak (2007)) and by manufacturers:

- Accelerated wear, possibly causing power loss, decreased reliability, increased maintenance needs and shortening of generator life. This can be due to the following operating conditions:
    - Sustained operations in low-load conditions. This leads to low heat in the cylinders and therefore to incomplete combustion and to the accumulation of unburned fuel and oil deposits. Negative impacts can be expected when the generator is operated below 30 % to 50 % of its nameplate capacity, depending on its design.
    - Frequent starts and stops (cycling) of the generator. Depending on its design, the impact of a generator starting can be equivalent to a few minutes up to several hours of continuous operation at rated load in terms of wear.
    - Repeated use of quick loading of the generator. This refers to an accelerated start-up of the generator that can reduce start-up time by about 80 % compared to regular start-up. The wear induced by quick loading can be particularly important if the machine is not sufficiently lubricated.
    - Use of heavy fuel oil as input fuel, rather than light fuel oil or gas oil. Although heavy fuel oil is less expensive than lighter fuels for the same energy content, its high viscosity typically leads to higher wear and intensifies the effects listed above.
- Higher fuel consumption and emission of pollutants (sulphur oxides and nitrogen oxides) due to incomplete combustion at part load. The increase in fuel consumption per produced kWh at 50 % loading is typically in the range of 3 % to 7 % compared to the fuel consumption at 100 % load.

inflexible by design[6], while gas-fired plants generally offer good levels of flexibility (unless their operation is constrained in co-generation arrangements for which heat production must remain constant).

- Some islands with rugged terrain and hydrological resources also include reservoir hydropower plants that can release the stored water to the water turbines when needed, therefore adding significant flexibility to the generation system.

- Other types of renewable energy sources for electricity (such as solar PV, wind, biomass, etc.) are already part of several SIDS power systems.

The flexibility characteristics of the different types of controllable generators are described in more detail later in this guide (see Chapter 5).

In addition to the technical characteristics of the generating units, contractual aspects (*e. g.,* take-or-pay clauses) can limit the potential to deploy available flexibility at some power plants. For example, decreasing the power output may not be permitted (and potentially subject to high penalty costs) for some baseload assets. A maximum number of yearly start-up/shutdown cycles might also be contractually constrained for some generators.

Given the large diversity of possible situations, it is difficult to define a single indicator or formula to measure the flexibility of generation systems. However, a qualitative assessment often can be made based on the generation technologies that are used.

Systems with high flexibility generally are considered to be less vulnerable to VRE variability and uncertainty given that their generation can be controlled on demand to avoid such issues. However, even for flexible systems, performing some dedicated studies may still be needed to estimate the operational cost of VRE integration or to detect if flexible generators would not be subject to excessive cycling or to too-frequent operation at low load.

Although there is no "one-size-fits-all" criterion, assessing the following set of triggering conditions can be considered if there is a plausible risk that a given generation expansion scenario could lead to technical issues due to lack of flexibility:

- VRE generation is expected to reach a significant share of the instantaneous total power demand on the island in some periods. A typical threshold often found in the literature and in the operational codes of some islands (including, for example, most island territories of France) is 30 % instantaneous penetration of VRE. However, this is highly dependent on the local context, and generally it is safer to start conducting studies for lower VRE penetrations (see Section 3.4).

- There are some periods during which VRE could supply more than the instantaneous local load on any given sub-part of the grid (*e. g.,* on a given distribution feeder).

- A significant share of the electrical energy is produced by conventional generators that are either inflexible by design (*e. g.,* coal power plants) or subject to operational constraints preventing them from being flexible (*e. g.,* co-generation schemes, technical condition due to ageing, contractually binding baseload operation, technical minimum, etc.).

Considering the diversity in island power system characteristics, it is impossible to define precise quantitative rules that would be applicable in all cases. The above conditions should be taken as general guidance rather than as strict rules for the planning and operation of SIDS power systems with VRE. They can provide signs that some issues could occur in the system and that specific studies should be carried out. Only after the studies are done can a final conclusion on the technical feasibility of the proposed generation expansion scenario be reached.

6 However, some flexible designs are increasingly being adopted for new coal plants.

2.2. Demand and load profile

The ratio between instantaneous VRE share and instantaneous electricity demand (either locally or for the whole system) is key when assessing the system impacts of VRE integration. Therefore, the behaviour of the electrical load in the system, and in particular the shape of the load profile, is critical and should be understood when preparing planning studies.

Combining a system load profile with the expected VRE generation profiles makes it possible to determine the net load that needs to be supplied by the other non-VRE generators. Two main types of interactions between the load and VRE generation profiles are important to consider when assessing the impact of VRE integration:

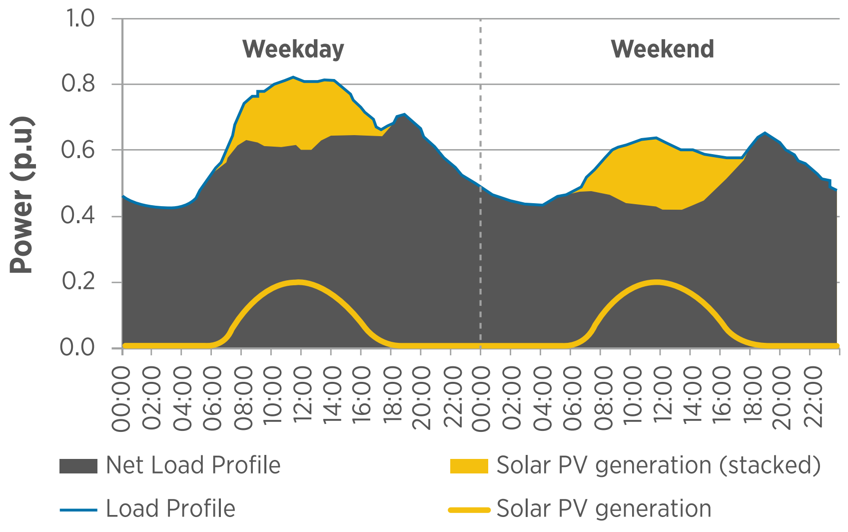
- The level of the minimum load in the system and its periods of occurrence. If VRE production occurs at these times, a risk of surplus (*i. e.,* negative net load) can exist, leading to several challenges, either at the system level (need to curtail VRE, lack of operating reserve and stability risk) or in a specific location of the grid (overloading or voltage issues). Correlation between the load level and VRE production can either aggravate or mitigate potential issues. For example, the positive correlation between solar PV generation and air conditioning loads in warm hours is beneficial. In other words, the challenge of integrating additional VRE depends on the load profile in the system and also on the type of appliances that are installed (air conditioning, electric heating, etc.).

- The presence of sharp increases or decreases in the load level over time (ramping events), such as load increase in the morning or load decrease at night. VRE generation can amplify these ramping events, or even create new net load ramping events on its own. An illustration of ramping needs induced by the decrease in solar PV output in the evening can be seen in Figure 5 in Section 2.1. The magnitude of this effect will depend on the share of VRE.

As shown in Figure 6, typical load profiles of island power systems are generally different on weekdays and weekends. Power consumption during working hours (daytime hours) is normally much lower during weekends. This leads to different impacts of VRE on the net load. For example, the increase in evening ramping needs due to solar PV will be more pronounced during weekends.

Given the above aspects, one can easily understand the potential benefits of generation flexibility for power

Figure 6: Illustration of solar PV impact on net load during the weekday and weekend for SIDS



Based on IRENA, 2015d, unpublished.

system operation. This flexibility is usually provided by the generating units, as explained in the previous section. However, demand-side flexibility (or demand response) is also a flexibility resource that could be employed to improve VRE integration. Being able to impact the consumption profile of some consumers could help in avoiding VRE surplus or in accommodating ramping events. Such solutions are discussed further in Chapter 9.

For power system planning engineers, it is crucial to understand the interactions between the load and VRE production for their respective power systems. After all, these interactions determine the way in which the power systems are operated. Moreover, the interaction between load and VRE is an essential input for each technical planning study, whether it concerns the sizing of reserve requirements, the scheduling of generation, or the static and dynamic network studies. Such studies are discussed further in Chapters 4, 5, 6 and 7.

The long-term context of load evolution also has impacts on the challenge of VRE integration. For example, it generally will be easier to integrate a given VRE capacity in a system with high yearly load growth (*e. g.,* a context of economic development) than in a system in which the load is decreasing (*e. g.,* in the case of an economic downturn or due to energy efficiency measures). This is simply linked to the decrease or increase of the VRE penetration induced by such evolutions.

2.3. Structure and characteristics of transmission and distribution networks

The structure of distribution and transmission networks in island power systems is also key when assessing the integration of VRE.

SIDS electrical networks can vary from very simple networks, with only a few medium-voltage distribution feeders, to larger systems including a high-voltage backbone transmission grid and possibly interconnections with other systems. This diversity is illustrated in Table 1, which presents four typical SIDS power systems with varying sizes, grid structures and generation mixes (IRENA, 2016a, 2015c, 2015d, 2015e).

For the purpose of this guide and given the specific nature of small-island power systems, the distinction between transmission and distribution networks will be made on a functional basis rather than based on voltage levels. The distribution grid comprises the low-voltage grids, to which residential and commercial customers are connected, as well as the voltage level just above (typically medium voltage). These networks typically have a radial structure.

Table 1: Characteristics of four islands representative of power system diversity in SIDS

Name	Generation fleet	Grid
Aitutaki (Cook Islands)	Installed capacity: 3 × 900 kilovolt-amp (kVA) generators in a single station	• 4 × 11 kV radial feeders from power station to the customers
Upolu (Samoa)	25 MW in main diesel station plus around 10 MW of hydropower installed	• 33 kV transmission lines connecting power plants and load centres • 22 kV radial feeder distribution
Antigua (Antigua and Barbuda)	Most of the generation (above 100 MW total installed capacity) located in a sub-station away from main town	• 69 kV transmission ring around the island • 11 kV radial feeder distribution
Dominican Republic	Installed capacity of about more than 3.5 gigawatts throughout the country, including large-scale natural gas-fired power plants	• 138 kV transmission network with 4 operational areas (2 around the major cities with 138 kV rings, 2 with radial 138 kV connection) • 345 kV line connecting the two areas with highest consumption

Source: IRENA, 2016b; 2015e, unpublished; 2015d, unpublished; 2015c, unpublished.

The transmission network is the part of the system dedicated to carrying power between distant load and generation centres. It generally is organised in a meshed structure or a ring structure to be able to continue operation in case of outage of a single transmission element (N-1 reliability criterion for the transmission system). On this basis, voltage levels of 30–36 kV can be considered as transmission networks in some SIDS, whereas these levels would be identified as distribution networks in larger systems. In this document, the ring structure is assimilated to the meshed structure (*i. e.,* it is the simplest meshed structure), even if a ring structure can be operated in an open loop.

Most of the grid-related technical constraints listed in Section 1.4 are applicable to both transmission and distribution grids. However, some specific issues are applicable only to one or the other, including:

For distribution:

- **Phase imbalance**, which generally is constraining only in low-voltage grids (*e. g.,* when large amounts of distributed generation are installed, such as in households or small commercial premises).

- **Protection malfunctions**, due to reverse flows (*e. g.,* power flow going from the distribution system to the transmission system to higher production of distributed resources than demand on the feeder), or low fault currents.

- **Voltage profile**, or dependence of the voltage on active power flows due to higher resistance of low-voltage networks[7] (*e. g.,* production of active power may lead to high increases in the voltage along the feeder and to corresponding variations when the production decreases).

- **Cycling of voltage control equipment** (*e. g.,* automatic tap changers on transformers), as voltage control equipment may have to operate in more cycles as it aims to manage variations produced by the injection of active power in the feeders.

For transmission:

- network overloading
- system stability
- voltage control due to reduced reactive power capability of VRE sources.

Network strength plays a fundamental role in the integration of VRE:

- A weak grid, characterised by a radial or poorly meshed network (see Figure 7) and high electrical distances between generating units and between generating units and loads, introduces several constraints for the integration of VRE. Weak grids usually present low transient stability margins and high voltage sensitivity with respect to load fluctuations.

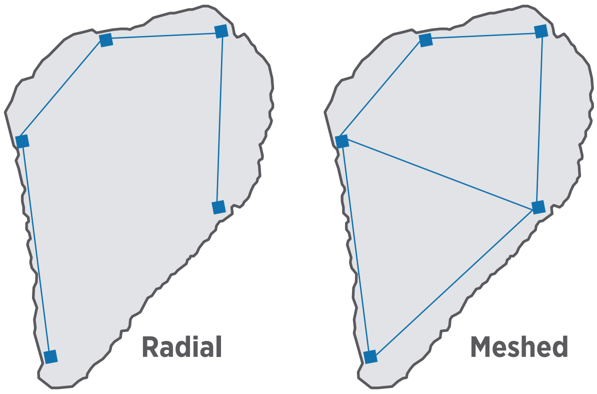
- A strong grid, on the other hand, is characterised by a highly meshed system with shorter electrical distances between generating units and loads. These grids usually are much more robust in terms of transient stability, and present lower sensitivity of voltages with respect to load variations.

Large electrical impedance between the load and the generation implies significant voltage variations at the load level when the power consumption changes, while low impedance leads to small voltage variations. Similarly, the transient stability relates to the stiffness of the link between synchronous generators. If the electrical distance is big, the stiffness is low and generators are more prone to loose synchronism in case of faults. On the contrary, if electrical distances are small, the stiffness is high.

Therefore, the network structure is a key element for the selection of the studies that need to be carried out to plan the system for VRE integration.

7 Voltage drop across a transmission element is the sum of the product of the reactive current by the reactance of the element and the product of the active current by the resistance of the element. When in high-voltage networks, the resistance is very small compared to the reactance, and the contribution of the second term is thus negligible. This is not the case for low-voltage networks.

Figure 7: Illustration of radial and meshed island grids



In addition to this distinction of issues applicable at either the transmission or distribution level, the specific characteristics of network elements (*e. g.,* electrical and thermal characteristics) influence the level of local VRE penetration that can be reached without leading to technical issues. For example, distribution feeders with a high resistance, through either a long length or low cross sections, will experience congestions or voltage issues at lower penetration than those with low resistance. Protections and voltage regulation equipment (*e. g.,* capacitor banks) also can impact the integration of VRE.

2.4. Variable renewable energy implementation strategy and generation expansion plans

Section 1.5 describes the optimal way to plan VRE integration to overcome technical challenges. However, the characteristics of generation expansion scenarios for the future deployment of VRE generators also have a significant impact on potential technical integration challenges. The main questions to consider are the following:

- Will dispatchable (possibly thermal) generators be decommissioned to be replaced with VRE?
- What is the future mix of VRE technologies expected in the system? How will this mix impact integration in the system considering the variability, limited predictability and less synchronous generation characteristics of VRE (explained in Section 1.4)?
- What is the future geographical location of VRE generators in the network?

On the one hand, with regard to the strategy used during planning, the systematic replacement of dispatchable generation with VRE is sometimes envisaged to have a critical impact on flexibility issues. Consequently, this must become a key consideration in implementation strategies. As mentioned in Section 2.1, even if there is no "one-size-fits-all" criterion for flexibility, a qualitative assessment of the impact on system flexibility of replacing dispatchable generators has to be performed.

On the other hand, depending on the available local resources and on envisaged strategies, VRE deployment in islands can either be concentrated on a few sites and technologies (*e. g.,* one large wind farm) or be very diverse in technologies and geographical locations. As the variability of the VRE fleet is generally smoothened with diversification, the probability of VRE-induced flexibility needs is reduced with the diversification. From a network perspective, different challenges can be expected from utility-scale concentrated plants than from distributed VRE installations (see Section 9.1). In particular, as described in Section 1.4, highly concentrated generation leads to transient stability issues.

In an ideal planning process, these aspects should already be considered when defining the generation expansion scenarios, as part of a comprehensive generation expansion plan.

However, the strategy may differ depending on the approach used for system transformation. In some cases, the VRE integration is achieved thanks to a single big project, while in other cases the transformation is done gradually through different projects implemented by a variety of stakeholders. In the first case, the implementation strategy can be controlled and organised relatively easily, but when different stakeholders control the potential VRE developments, implementation becomes much more difficult. When the development is progressive, planning studies and grid codes (or connection rules) are critical, as they will guide the entity in charge of the system development in achieving the implementation strategy without threatening the security of supply and the safe operation of the system.

2.5. Expansion and operational planning practices

The integration of high shares of VRE requires proper expansion and operational planning practices, as well as a clear and precise regulatory framework.

Defining the expansion and operational planning rules that allow for safe integration of VRE is a pre-requisite for successful power system transformation. Harmonisation of practices at the regional level would also be very advantageous for all stakeholders.

However, while such practices are relatively standardised among countries or regions that are part of large interconnected systems (*e. g.,* the ENTSO-E system in Europe), they can vary widely from one small-island power system to another. Planning practices also are strongly related to the institutional framework.

As a consequence, the practices applied by utilities in SIDS may lead to other limitations to the integration of VRE, in addition to just physical ones. Examples of practices that can constrain VRE integration include:

- Absence of dedicated long-/mid-term expansion planning activities or operational (day-ahead) planning with all decisions being taken in real time by system operators. This results in absence of planning criteria (both expansion and operational), directly impacting the amount of VRE that could be integrated into the system.

- Inadequate set-up of load shedding schemes, leading to difficulties in maintaining system stability in case of large instantaneous load/generation variations.

- Absence of sufficient operating reserves maintained in the generation dispatch to ensure system stability after the loss of a large generator (N-1 criteria). This is often the result of a lack of available generation capacity or of reduced operating costs (the cost of maintaining spinning reserve being potentially high if part-load operation of thermal generators is needed).

- Fully automated operation of diesel power stations to reduce fuel consumption while not taking into account varying reserve needs due to VRE.

- Absence of up-to-date grid-codes with clear definition of technical criteria for the connection of VRE sources that may lead to investing in a cheaper power plant design with limited (or no) control function (voltage, reactive power, active power, frequency, etc.), which contributes to degradation of the power system's reliability.

2.6. Influence of governance on technical operation

The organisation of the electricity sector, the power market design (if any) and the associated regulatory framework all affect the ability of the power system to accommodate high VRE shares. This section focuses on the influence of governance on the technical operation of the power system in the presence of VRE.

The structure of the electricity sector can be categorised in different stages, starting from a purely vertically integrated utility to a fully liberalised and unbundled electricity market (World Bank, 2011):

- ***Vertical integration:*** a vertically integrated monopolist responsible for generation, transmission (if any), distribution and retail of electricity.
- ***Vertical integration with independent power producers (IPPs):*** a vertically integrated monopolist accompanied by IPPs that sell power to it.
- ***Some extent of vertical and horizontal unbundling:*** a transmission entity formed from unbundling the monopolist acting as a single buyer of power from the generators and IPPs and selling power to distribution entities and large users of power.
- ***Power market:*** an organised market of generation entities, distribution entities and large users in which power is traded competitively, supported by a transmission entity, a power system operator and a power market administrator.

Due to their limited size, most SIDS are currently at stage 1 or 2, without specific needs to evolve to further stages.

For the SIDS that are archipelagos, two organisational schemes can be observed:

- In some cases, different utilities are in charge of grid operation in different groups of islands in the archipelago (for example, in Vanuatu and the Bahamas).
- In other cases, a single vertically integrated utility company is responsible for providing electricity on multiple islands within an archipelago (for example, in Saint Vincent and the Grenadines and the cayes of Belize).

Note that independently of the organisation scheme on one island, it is still dominated by a single vertically integrated utility, which does not, however, exclude the presence of IPPs or other players on the island (stage 2 of liberalisation process).

However, in several islands the opening of the market to IPPs has not being implemented alongside a proper regulatory framework, especially in the context of the energy transformation.

- IPPs can make real-time balancing and management of the power system more complex, especially in the presence of a high share of VRE. Ensuring power system reliability and security requires well-functioning interfaces between the actors and frequent exchange of the necessary information, highlighting the need for a clear regulatory framework.
- The regulatory and contractual obligations have to be adapted to the structure adopted on the island and to the type of project to avoid having these obligations affect the ability of the system to address the technical challenges related to VRE integration. The conditions of traditional power purchase agreements (PPAs) between generators and the single buyer can, in some cases, be too rigid to accommodate VRE, because of contractual inflexibilities that would not have been present in the case of a fully integrated electricity company.

- Finally, the possible solutions to VRE integration issues are different in instances where the generators are separate entities from the system operator. While changing the internal strategies and procedures used to operate existing generators (possibly with some equipment investments) could be an option for vertically integrated utilities, if independent generators are present, the same effects could be achieved only through a modification of PPA or grid code requirements. This, for example, concerns the level of participation of generation units to frequency or voltage control as well as the possibility of curtailing some VRE generation if there is stress in the system.

This analysis justifies the need to develop a regulatory framework that takes into account the structure of the electricity sector at the island or archipelago level and that supports VRE integration.

2.7. Synthesis

This chapter described the main characteristics of small-island power systems that are essential when planning the integration of VRE. Six main topics were addressed:

- the flexibility of existing and future power generation fleets
- the demand and load profile
- the structure and strength of transmission and distribution networks
- the VRE implementation strategy and generation expansion plans
- the expansion and operational planning practices of small-island utilities
- the influence of governance on technical operations.

A key aspect for SIDS will be grasping the technical challenges associated with VRE integration (mainly generation adequacy, intraday flexibility, stability, static thermal/voltage grid limits, short circuits and protections, and power quality) while considering the main characteristics of their power systems.

Table 2 illustrates the synthesis mapping between the power system characteristics, discussed in this chapter, and the technical challenges discussed in Section 1.4.

It shows the importance of considering the specificities of small-island power systems when capturing the technical challenges of VRE integration.

To succeed in the SIDS transformation, it will be essential to develop a solid framework that will support VRE integration, notably by describing technical assessment of VRE integration in small-island power systems. This technical assessment is discussed in the next chapter.

Table 2: Mapping of power system characteristics with technical challenges of VRE integration

	Integration challenge					
System characteristic	**Generation adequacy**	**Intraday flexibility**	**Stability**	**Static thermal/ voltage grid limits**	**Short circuits and protections**	**Power quality**
Flexibility of existing and future power generation fleet	Medium Impact	Medium Impact	High impact	Medium Impact	Low or no Impact	Low or no Impact
Demand and load profile	High impact	High impact	High impact	High impact	Low or no Impact	Low or no Impact
Structure and strength of transmission and distribution networks	Medium Impact	Medium Impact	High impact	High impact	High impact	Medium Impact
VRE implementation strategy and generation expansion plans	High impact	High impact	High impact	High impact	High impact	Medium Impact
Expansion and operational planning	High impact	High impact	High impact	High impact	High impact	Medium Impact
Influence of governance on technical operations	High impact	High impact	High impact	High impact	High impact	Medium Impact

Legend: **High impact** | **Medium Impact** | **Low or no Impact**

3. POWER SYSTEM PLANNING FOR VARIABLE RENEWABLE ENERGY INTEGRATION

Power system planning can be divided into two categories: expansion planning and operational planning.

Expansion planning deals with the problem of which investments in new generation capacity and network infrastructure should be done (and when) in order to adequately supply the forecasted demand. The time horizon of expansion planning ranges from months to a few years (mid-term planning) up to about 10 years (long-term planning)[8].

In operational planning, which covers the short-term horizon, investment in new generating units or networks is not possible. In this case, the only control means available to the operator are the operational set-points of the already existing equipment, as well as their operational practices.

Power system planning in small islands is very challenging due to the following:

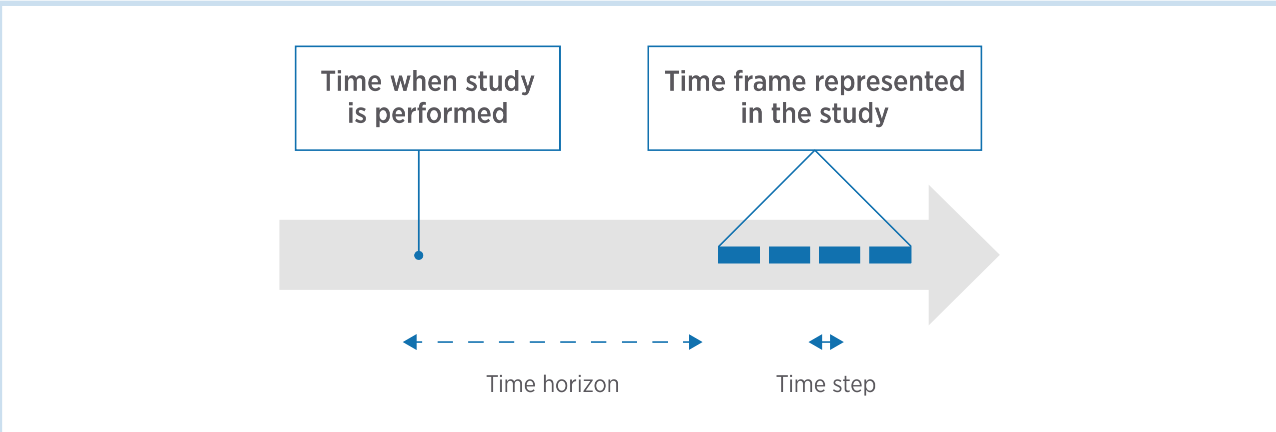
- ***Expansion planning:*** limited primary resources available in place for new generating units, environmental constraints for network expansion, high uncertainty on the electricity demand growth, etc.
- ***Operational planning:*** small system inertia, high sensitivity of network voltages and system frequency with respect to small variations of the load and renewable energy generation, protection selectivity, forecasting of renewable energy production, system reliability, etc.

This chapter establishes the links between the power system characteristics of islands and the relevant technical studies that should be carried out when planning the systems for VRE integration. It introduces the main technical studies that can be relevant when planning the future integration of VRE in small-island power systems and then proposes a step-by-step approach to identify which studies are relevant for a given system.

In this guide, technical studies refer to analyses of possible power system operating conditions through simulation models representing different power systems phenomena that occur over different time frames (from a few seconds to multiple years).

For the purpose of this guide, the role of the technical studies is to link the challenges of VRE integration to the solutions that can enable such integration. The

Figure 8: Different time concepts for technical studies



8 Note that investments in new conventional generation take more time to implement than new investments in transmission. However, new VRE power plants are usually implemented in very short time periods.

studies help in identifying and quantifying the technical problems and challenges relevant to a given system. This process serves as a guide for the planning engineers to address such issues with adequate practices, methods and solutions.

The studies discussed in this guide can be categorised in three main groups based on 1) the time horizons at which they are generally carried out, 2) the types of phenomena they address and the elements of the power system that they represent and 3) the methodologies used to perform the analyses. The following types of studies are discussed in this guide:

- generation adequacy and reserve sizing
- generation scheduling
- network studies, including
  - static network analyses
  - dynamic network analyses
  - special network studies[9].

The guide covers both generation- and network-related studies, since most SIDS utilities are still vertically integrated and can plan both systems in an integrated way. The description of the different studies in this guide also can be read independently depending on the specific needs of the reader.

The different time concepts used in this guide when addressing technical studies are illustrated in Figure 8: The ***time frame*** is the time period that is represented by the mathematical model used in the study. It is related to the nature of the physical phenomena represented.

- This time frame is often broken down into multiple time periods, called ***time steps***, which represent successive states of the system. Some studies such as static network analyses use only a single time step (in this case identical to the time frame)[10].
- The ***time horizon*** is the period of time between the date at which the study is conducted (the date at the planning stage) and the future time frame that it considers.

Typical time horizons over which studies are performed for systems with VRE are presented in Table 3. The focus is placed on long-/mid-term planning (month to years ahead) and on operational planning (day to week ahead) since these are the most common planning horizons. Some assessments (such as load flows or generation scheduling) also can be made on shorter, intraday time frames (from hours ahead to near real time) but this is rarely applied in SIDS in practice.

As shown in Table 3, it is important to consider that some assessments can be performed for different time horizons, based on the best forecasts available at the time, although they aim to represent the same final time frame of the system. Despite the same types of studies being carried out for both expansion planning and operational planning, different analyses and conclusions are made depending on the planning horizon under consideration.

For example, load flow studies can be performed years in advance for grid planning purposes, based on long-term forecasts and scenarios of power demand and generation outputs in the different nodes of the network. The same load flow studies also can be done as part of the day-ahead operational planning activities of a utility to ensure that the generation schedule for the next day will not lead to overloads or voltage control issues.

Table 3 also shows which parts of the power system are generally modelled in the different studies. All studies include at least a simplified representation of load and generation, while only some of them require the representation of transmission and/or distribution grids. In addition, Table 3 provides indications on the applicability of the studies to SIDS.

9 The special network studies presented in this guide are a group of studies that are generally carried out only with a very specific purpose when planning VRE integration, such as defence plans and grid connection studies

10 This is common practice in distribution system studies.

Table 3: The main types of studies to support VRE integration

			Typical time horizon		Parts of the power system represented		
			Long-/mid-term planning (month to years ahead)	**Operational planning (day to week ahead)**	**Load and generation**	**Transmission**	**Distribution**
		Generation adequacy	Almost always applicable	Almost never applicable	Almost always applicable	Applicable in specific cases	Almost never applicable
		Sizing of operating reserves	Almost always applicable	Applicable in specific cases	Applicable in specific cases	Almost never applicable	Almost never applicable
		Generation scheduling	Almost always applicable	Almost always applicable	Almost always applicable	Applicable in specific cases	Almost never applicable
Network studies	Static	Load flow	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable
Network studies	Static	Static security assessment	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable	Applicable in specific cases
Network studies	Static	Short-circuit currents	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable
Network studies	Dynamic	System stability	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable	Applicable in specific cases
Network studies	Special	Grid connection	Almost always applicable	Almost never applicable	Almost always applicable	Almost always applicable	Applicable in specific cases
Network studies	Special	Defence plans	Almost always applicable	Almost never applicable	Almost always applicable	Almost always applicable	(UFLS & UVLS) – Applicable in specific cases

Legend: **Almost always applicable** | **Applicable in specific cases** | **Almost never applicable**

Note that expansion planning and operational planning activities are tightly linked. This means that inadequate system expansion planning may lead to several technical constraints for system operation, resulting in poor quality and in less affordable service provision. The same is valid for operational planning, which should ensure adequate feedback (return of experience) from system operation to the expansion planning process, with the objective of solving actual problems by means of appropriate future investments.

The roles of the different types of studies in the planning process are described in the following sections. Their potential use for expansion planning and/or for operational planning is also explained, as well as the links between them.

In this guide, it is assumed that a generation expansion scenario is already available to the reader for the considered SIDS (in other words, the generation expansion planning exercise has already been performed). This plan generally will have been based on a least-cost approach, possibly accounting for some targets to be met at certain time horizons (*e. g.,* a given renewable energy penetration target). The methodologies for least-cost generation capacity expansion planning are not discussed as part of this guide, but extensive literature is available on the subject. (For example, IRENA's System Planning Test model (SPLAT) is used for capacity expansion planning of the African Power Sector; see IRENA 2015f.) Theoretical background on generation expansion planning can be found in IAEA (1984), Stoll (1989) and Conejo et al. (2016).

In addition, the following sections map the technical studies used to tackle the potential technical challenges that may arise when integrating high shares of VRE in island power systems. Table 4 provides a summary of the main technical challenge addressed by each study discussed in this guide.

3.1. Generation adequacy and reserve sizing

Two types of studies that should be carried out either as part of the generation planning exercise, or as a direct follow-up to it, are generation adequacy studies and studies for sizing operating reserves. Both of these types of studies are relevant mostly at the long- and mid-term planning stages (months to years in advance)[11] and require only the analysis of future load and generation in the system (not the network).

Generation adequacy studies aim to ensure that the generation capacity available at a certain time horizon, including VRE, is sufficient to cover the forecasted load, while complying with pre-defined reliability criteria (*e. g.,* LOLE or EENS) in a given year. These studies require a statistical modelling of the availability of the different generators (including VRE) in order to compute the above-mentioned indices. Section 4.1 of this guide describes these studies in detail.

Table 4: Mapping of the technical studies and the VRE integration challenges addressed

Technical study \ Integration challenge			Generation adequacy	Intraday flexibility	Stability	Static thermal/ voltage grid limits	Short circuits and protections	Power quality
Generation adequacy			Almost always applicable	Almost never applicable	Almost never applicable	Almost never applicable	Almost never applicable	Almost never applicable
Sizing of operating reserves			Almost never applicable	Almost always applicable	Almost always applicable	Almost never applicable	Almost never applicable	Almost never applicable
Generation scheduling			Almost never applicable	Almost always applicable	Almost never applicable	Almost never applicable	Almost never applicable	Almost never applicable
Network studies	Static	Load flow	Almost never applicable	Almost never applicable	Almost never applicable	Almost always applicable	Almost never applicable	Almost never applicable
Network studies	Static	Static security assessment	Almost never applicable	Almost never applicable	Almost never applicable	Almost always applicable	Almost never applicable	Almost never applicable
Network studies	Static	Short-circuit currents	Almost never applicable	Almost never applicable	Almost never applicable	Almost never applicable	Almost always applicable	Almost never applicable
Network studies	Dynamic	System stability	Almost never applicable	Almost never applicable	Almost always applicable	Almost never applicable	Almost never applicable	Almost never applicable
Network studies	Special	Grid connection	Almost never applicable	Almost never applicable	Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable
Network studies	Special	Defence plans	Almost never applicable	Almost never applicable	Almost always applicable	Almost always applicable	Almost never applicable	Almost never applicable

Legend			
Legend	Almost always applicable	Applicable in specific cases	Almost never applicable

11 Sizing of operating reserves might be an exercise to be performed in operational planning as well, depending on the complexity of the system and the VRE penetration level.

The ***sizing of operating reserves*** is performed in order to define the level of operating reserve needed to accommodate short-term (intraday) variations and forecast errors related to load or generation profiles. It typically is conducted as part of long-/mid-term planning activities but also at the operational planning stage for more complex systems (*e. g.,* in day-ahead). It requires statistical examination of the possible variations of load and generation in the system at different timescales and defining the reserve levels to cover an acceptable risk of variation. Section 4.2 of this guide describes these studies in detail.

3.2. Generation scheduling

Generation scheduling is generally performed on a day- or week-ahead basis for the unit commitment and economic dispatch of the dispatchable generation units in the system, based on the forecasted load and VRE output. In the presence of VRE, generation scheduling studies also should take place as part of the long- and mid-term planning, which improves the quality of the plan, possibly avoiding operational issues later on. In both cases, generation scheduling serves the following purposes for VRE integration:

- ensuring that the generation system is sufficiently flexible to accommodate expected variations in the net load (*i. e.,* the forecast demand profile over the next day(s) minus the forecast VRE generation profile) while maintaining the required operational reserves;
- evaluating the impact of VRE integration on operational generation costs (and possibly pollutant emissions), considering:
    - the decrease in operational generation costs (or emissions) due to displacement of thermal generation with VRE, and
    - the increase in operational generation costs (or emissions) due to more frequent operation of thermal generators at part load or higher cycling of units (start-up/shutdown).

The technical characteristics of the generating units have to be taken into account in such a study, including minimum technical operating level, minimum up/down time, start-up time, ramping constraints, etc. Furthermore, reserve requirements significantly influence the outcome of generation scheduling and complicate solution of the problem. Typically, reserve requirements include N-1 criterion of generating units.

Generation scheduling studies are detailed in Chapter 5 of this guide.

3.3. Network studies

Detailed network studies are needed to assess how the power system will behave under expected and unexpected conditions and to ensure secure, stable and reliable operation.

These studies can be classified into three main categories:

1. ***static network studies:*** analysis of the steady-state operating condition of the network;
2. ***system stability studies:*** analysis of the dynamic behaviour of the system when facing incidents (short circuit, load variation, generation tripping, etc.);
3. ***special studies:*** analysis of specific phenomena (harmonics, resonance, voltage fluctuations, etc.), equipment protection or system-level protection.

Static network studies

Static network analyses generally are the first step in modelling the impact of VRE integration on the network. Compared to the assessments discussed in the previous sections, which focus mainly on generation and load interactions, these studies require modelling the details of the network in which VRE will be integrated, either at the transmission or distribution level.

These studies can be performed at different time horizons, from long-term planning to near real time. In expansion planning, the objective of static studies is to determine the required network reinforcements in order to supply the expected load without overloads or network congestions, as well as without violating voltage constraints. In short-term planning, the objective is to determine if the planned generation schedule is adequate to supply the forecasted load without network overloads and to set up proper voltage profile in the network. In instances where overloads are detected, generation rescheduling might be needed.

These studies are referred to as "static" because they consider only a single state (snapshot) of the system and not a dynamic evolution over multiple successive time steps.

Three main types of studies are considered within static network analysis:

- load flow (normal condition)
- static security assessment (contingency analysis)
- short-circuit currents.

Load flow studies (see Section 6.1) aim to determine the voltages and power flows through the network under normal operating conditions given a pre-defined generation dispatch and expected load distribution. The outcomes of these studies make it possible to assess the network's capability to supply a given load with a given generation dispatch scenario without violating any voltage limit or overloading any system equipment.

Static security assessment studies (see Section 6.2) aim to determine the voltages and power flows through the network under contingency conditions in order to identify potential overloads or violations of voltage limits. In SIDS, only the most probable contingencies, also known as normative incidents[12] (based on a statistical analysis of past incidents in the network), are taken into account in order to avoid prohibitive operating costs or very expensive investments in network expansion for a marginal improvement of system security.

Short-circuit current studies (see Section 6.3) aim to ensure that no violation of equipment short-circuit current rating occurs, as well as to guarantee a minimum short-circuit power at the point of connection of VRE generators. The contribution of VRE to the short-circuit current generally differs from the contribution of conventional power plants equipped with synchronous machines.

The specific objectives of each type of static study may differ during expansion planning and operational planning. Those objectives are as follows:

- Expansion planning:
  - ***Load flow and static security assessment:*** determine the required network reinforcements in order to supply the forecasted demand without network overloads or congestions, as well as without violating voltage constraints.
  - ***Short-circuit currents:*** determine possible upgrades of existing equipment (busbars and circuit breakers), as well as provide specifications for new equipment.

- Operational planning[13]:
  - ***Load flow and static security assessment:*** In instances where overloads are detected, generation rescheduling is needed (including VRE curtailment).
  - ***Short-circuit currents:*** in instances where the short-circuit current capability of equipment is violated, network switching (change in the network topology) should be implemented to reduce the short-circuit currents. On the other hand, in instances where insufficient short-circuit levels are detected, dedicated mitigation measures need to be implemented to assure protection co-ordination and selectivity. (For more details see Chapter 6.)

Note that in small to medium-size SIDS, network studies for operational planning need to be carried out only when significant changes to the system occur (*i. e.,* commissioning of new equipment, generating unit out of service for maintenance, etc.), given the simplicity of the network topology.

12 Also known as secured incidents.

13 In SIDS, these grid studies need to be carried out only when significant changes to the system occur (*i. e.*, commissioning of new equipment, generating unit out of service for maintenance, etc.).

System stability analyses

These studies aim to represent the dynamic behaviour of the power system in the presence of VRE to check that the system is sufficiently stable. The three main types of stability discussed in Section 1.4 are represented in these studies:

- frequency stability
- transient stability
- voltage stability.

These studies are referred to as "dynamic" since they consider the dynamic evolution of the system state over time.

Additional details on the dynamic behaviour of the system (*e.g.,* control schemes of generators) are considered when performing these studies. A detailed guide on how to perform system stability analyses for small-island power systems is presented in IRENA (2015a) and Sigrist et al. (2016). In the framework of this guide, more information on stability studies and the methodology on how to perform them are presented in Chapter 7.

As with static network studies, the specific objectives of each type of stability study may differ for expansion planning and operational planning. These objectives are given as follows:

- Expansion planning:
  - ***Transient stability:*** assess the adequacy of the planned network structure and protection schemes in order to avoid transient stability problems. In case the transient stability margin is insufficient, a review of the proposed network reinforcement plan needs to be performed.
  - ***Frequency stability:*** assess if large frequency drops are detected due to the lack of inertia, resulting in the activation of under-frequency load-shedding (UFLS) schemes, partial blackouts or a system collapse. Required measures might include the implementation of synthetic inertia function to the VRE power plants, an automatic generation control scheme, improvement of UFLS settings and/or deployment of energy storage for frequency control purposes.
  - ***Voltage stability:*** assess the adequacy of the voltage/reactive power compensation schemes in order to face disturbances without resulting in voltage collapse. In instances where voltage instability is detected for given conditions, new investments in reactive power compensation means might be required.

- Operational planning[14]:
  - ***Transient stability:*** assess if the planned operating conditions are able to withstand faults cleared in base time. In case this condition is not fulfilled, generation re-dispatch (including VRE curtailment) or modification to the voltage set-points of the generating units can be envisaged.
  - ***Frequency stability:*** assess if the operational reserves are adequate to assure stable system operation from the point of view of frequency control. In case reserves are not sufficient to avoid massive load shedding or system collapse, generation re-dispatch (including VRE curtailment) and/or improvement of UFLS settings can be envisaged.
  - ***Voltage stability:*** assess if the planned operating conditions are adequate to assure stable system operation from the point of view of voltage. In instances where voltage instability is detected, a review of the voltage/reactive power compensation scheme should be carried out.

Special network analyses

The special studies presented in this guide regroup studies that generally are carried out only with a very specific purpose when planning VRE integration or for systems with particular characteristics. A detailed methodology on how to perform these special studies is presented in Chapter 8.

14 In SIDS, these grid studies need to be carried out only when significant changes to the system occur (*i. e.*, commissioning of new equipment, generating unit out of service for maintenance, etc.).

Defence plan analysis aims to define special protection schemes (SpPS) to allow the integration of VRE while assuring system security. This includes, for example, the definition and settings for UFLS and under-voltage load-shedding (UVLS) schemes. Defence plan studies are performed in mid-term planning studies in order to determine the adequate defence schemes and actions to ensure that the planned system is secure for operation. Review of the defence plan studies may take place in short-term planning every time that operational results show inadequate behaviour of these SpPS.

Grid connection studies are carried out during the development phase of new generation assets. Whether it is a conventional unit or VRE, a grid connection study must be carried out. This study is usually divided into two parts:

- ***Grid impact study:*** aims to verify whether the existing electricity system is capable of integrating the new generating unit, and
- ***Grid code compliance study:*** aims to verify whether the new installation is compliant with the various grid code requirements.

Power system model for network studies

Performing static (steady-state condition) and system stability (dynamic condition) studies requires the development of a power system model. The mathematical models used for these types of studies are usually implemented in power system simulation tools, leaving to the planning engineer the task of feeding these mathematical models with proper input data that describe the physical characteristics of the real power system equipment (generators, lines, transformers, loads, etc.) of the system under study.

The data needed to feed into the power system simulation tools are usually provided in equipment datasheets and in commissioning or test reports. However, to ensure that the models represent the real physical behaviour of the system, it is recommended to validate the model by comparing simulation results with data obtained through field tests and measurements during normal system operation.

Additional information on model validation for system stability analysis is described in IRENA (2015a). Specific models and data required for each type of study are presented in Chapters 6 to 8.

Selection of scenarios for network studies

Static and system stability analyses are performed on a single initial system state. This state is defined by the topology of the network, by the dispatch of the generating units and by the load at each point of the system. Because the number of possible states is huge, a methodology for selecting the most representative ones is necessary. Once selected and built, these scenarios can be studied according to the methodologies detailed in Chapter 6. This analysis should be performed based on the analysis of time-synchronised load and VRE generation time series and aims to determine the most representative states of the system for detailed static and dynamic analyses. Usually, the most relevant scenarios for VRE integration studies are the following:

- Peak load:
  - no VRE generation
  - maximum VRE generation[15]

- Minimum load:
  - no VRE generation
  - maximum VRE generation[16]

- Minimum net load[17]

Scenarios without VRE are needed to assess the challenges/problems that might occur even without the presence of VRE. The comparison of results with and without VRE allows for identification of the problems and challenges related exclusively to VRE integration.

15 If peak load is during the evening or night, solar PV generation is equal to zero. In this case, only other VRE sources must be considered.

16 If minimum load is during the evening or night, solar PV generation is equal to zero. In this case, only other VRE sources must be considered.

17 Although this scenario could be equivalent to the one of minimum load with maximum VRE generation in a few cases, this would only occur if the period of minimum system load corresponds to one of maximum VRE generation.

The analysis of the peak load condition is important because this condition usually results in the highest power flows through the network. Minimum load condition is challenging from the point of view of voltage control/ reactive power compensation. The minimum net load is especially important for VRE integration studies because, at this condition, the amount of conventional generating units synchronised to the network is minimum, resulting in a worst-case condition from the point of view of system stability.

The selection of scenarios can be implemented easily in a spreadsheet environment. The input data needed for the definition of the scenarios may include the following: time-synchronised hourly or sub-hourly load, solar irradiation, wind speed and water inflows time series plus results of generation scheduling plus results from the sizing of operating reserves. These data usually are obtained as result of a generation scheduling study, as presented in Chapter 5. The outcomes of the definitions of the scenarios are the generation dispatch and load at each node of the system.

3.4. Identification of required technical studies in a given small island developing state

This section synthesises how the characteristics of a given small-island power system influence the studies that are needed to plan for VRE integration.

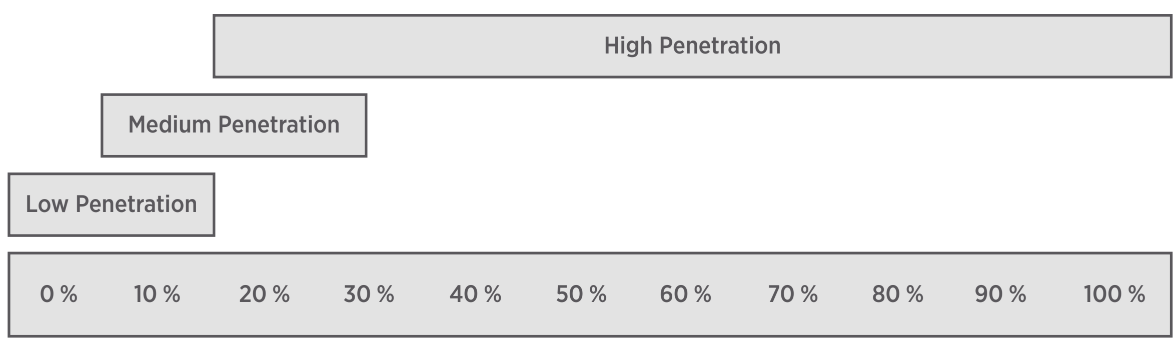
VRE penetration levels

When selecting the technical studies to plan for the integration of VRE in a given small-island power system, the first question concerns the targeted or expected level of VRE penetration at the system level, chosen *ex ante* by the system planner to assess VRE hosting capacity or defined in the framework of the generation expansion planning and thus taken as input in this guide. The maximum instantaneous penetration of VRE generation compared to the load is the most relevant metric for this purpose. Three qualitative levels of maximum instantaneous VRE penetrations are used in this guide – low, medium and high – following the same approximate ranges as in IRENA (2013). They are shown in Figure 9.

The threshold VRE penetration between low, medium and high penetration would typically vary from one system to another, which is why overlapping ranges are used. In addition, notably, the overall penetration at system level does not necessarily reflect the local penetrations in the different parts of the network (*e. g.*, penetration can be low at the system level, but high in some distribution feeders).

If at any point in time the share of VRE generation stays below about 10–15 % of the total instantaneous load, the VRE penetration can be described as low and no significant integration issues are generally expected. However, this does not necessarily mean that no study is required, as explained below.

Figure 9: Approximate ranges of VRE penetrations



Source: IRENA, 2013.

Required studies

For low penetration levels, only dedicated grid connection studies for each of the planned VRE projects are needed. These studies are carried out during the development phase of new generation assets by the project developer (whether the utility itself or a private stakeholder). They typically include load flow (and static security assessment) and short-circuit studies. A compliance study with respect to the prevailing grid code or technical rules, also including power quality aspects, is often also required (typically for projects above a given size).

For medium and high levels of VRE penetration, the effects on the power system will need to be assessed through several of the studies listed previously. For these cases, the analysis should start with studies at the system level, considering only load-generation balancing needs. This includes studies of ***generation adequacy, operational reserve sizing, generation scheduling and frequency stability.***

If frequency instabilities are identified, a ***defence plan study*** is recommended to check whether the defence plan in place on the island (if any) is adequate to avoid a system collapse. If it is not adequate, possible modifications of this existing defence plan can be considered as part of the defence plan study (*e.g.,* revision of UFLS scheme). However, this is a corrective action to be applied only as a last resort, and other solutions can be investigated to avoid getting to this point (see Chapter 9).

If a transmission grid[18] is present on the island, the following studies would be applicable: ***load flows, static security assessment, short-circuit current study, rotor angle stability and voltage stability.***

As noted previously, the outputs of the stability studies might trigger the implementation (or revision, if it already exists) of the ***defence plan*** of the island (*e.g.,* UFLS, UVLS).

The last type of studies that could be needed are dedicated distribution studies. These would be required in case there is no transmission grid on the island or if a medium/high penetration of VRE is observed on the distribution grid. The distribution studies typically include ***load flow and short-circuit studies.***

Finally, if the targeted VRE deployment consists mostly of distributed generators to be connected via a single phase in low-voltage distribution systems (typical for solar PV), the distribution studies need to include ***unbalanced load flows*** to identify potential phase unbalance issues on distribution feeders.

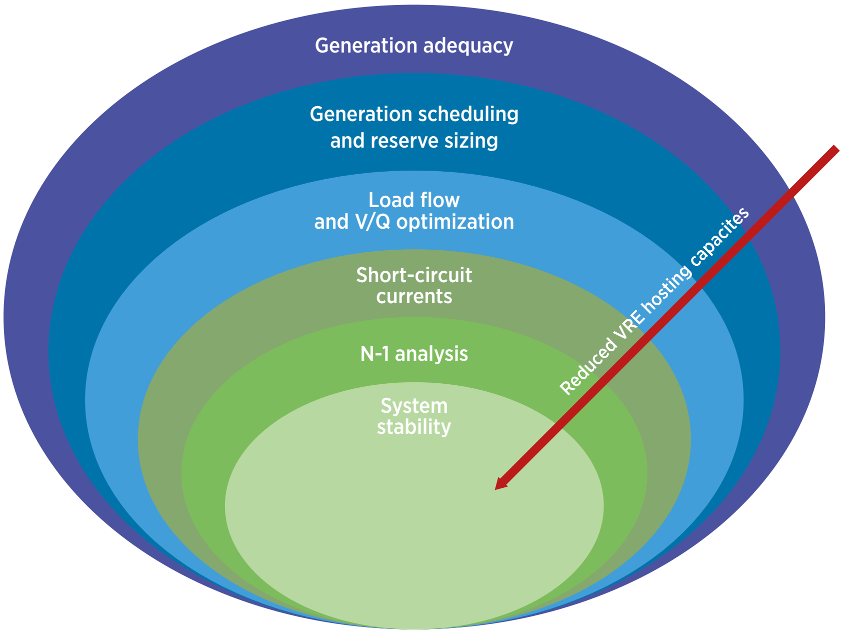
The portions of the distribution grid that have the highest VRE penetrations compared to the local load are naturally the first ones to be analysed in the distribution studies.

Performing the different studies presented above can make it possible to identify the maximum VRE hosting capacities of the power system for the different technical challenges assessed by each particular study. Generally, the output threshold penetration limits will not be the same for all studies. Ensuring that no technical issue would occur in the presence of VRE requires setting a global penetration limit for the grid (before the application of possible mitigation measures) equal to the minimum of the hosting capacities found in the different studies. This is illustrated in Figure 10, which presents a general example of the different degrees of limitation to VRE integration posed by different studies.[19] In this example, system stability studies would set the maximum VRE hosting capacity of the system.

18 For the definition of transmission network used in this guide, please refer to Section 2.3.

19 Order may vary depending on the characteristics of the SIDS system.

Figure 10: Limitations for VRE integration resulting from different technical studies



* Order may vary depending on the characteristics of the SIDS system

Grid connection studies

Grid connection studies are performed every time that integrating a new generating unit to the system is considered. There are two time horizons where a specific type of study is needed:

- during pre-feasibility phase of the project: grid impact study;
- a few months before the commissioning of the project (when the detailed design of the power plant is already finished): grid code compliance study.

3.5. Relationship between the different technical studies

Figure 11 describes the relationship between the different technical studies for which a detailed methodology is presented in this guide. Detailed information for each type of study is given in Chapters 4 to 8.

Details about the evaluation criteria, output information and solutions depicted with numbers in the figure, for both expansion planning and operational planning, are given in Table 5.

Figure 11: Sequencing and relationships among the different technical studies

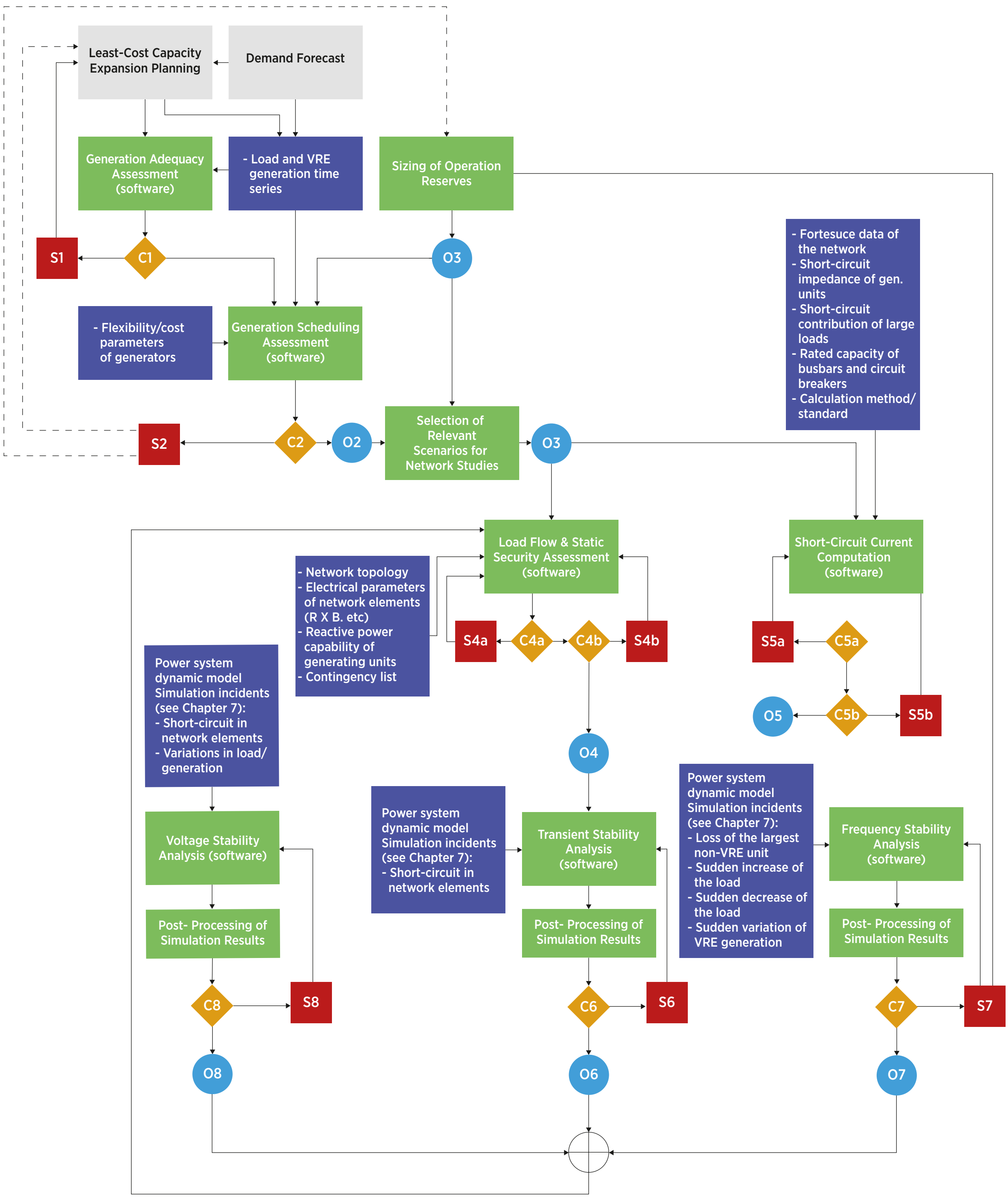


Table 5: Description of elements for the technical studies flowchart

Study		Evaluation criteria (C)	Main outputs (O)	Solutions (S)	
				Expansion planning	Operational planning
Generation adequacy and sizing of operating reserves	1	• Loss of load expectation requirement exceeded?	• Required operating reserve size (possibly dependent on time) and sizing events (*e.g.*, net load ramping due to VRE variations)	Investment in new capacity (generation, storage, demand response, network reinforcement, etc.) to the system	Not applicable
Generation scheduling assessment	2	• Acceptable level of operational costs? • Acceptable level of VRE curtailment? • Acceptable level of violation of operating reserve requirement or load shedding due to lack of generation flexibility?	• Generation dispatch scenarios	• Adding flexibility to the system through investments in new infrastructure (*e.g.*, storage) and/or operational measures (*e.g.*, modified generation dispatch and control)	• Adding flexibility to the system through operational measures (*e.g.*, adapted generation dispatch and control) • Limits to VRE injection (VRE curtailment) • Increased operating reserves
Selection of relevant scenarios for network studies	3	Not applicable	• Peak load: - No VRE generation - Maximum VRE generation • Minimum load: - No VRE generation - Maximum VRE generation • Minimum net load • Other relevant scenarios	Not applicable	Not applicable
Load flow and static security assessment	4a	• Violation of voltage limits?	• Voltage magnitude and phase at each node • Power flows (active and reactive) through each element of the network • Power injections at each node • Network losses • Phase unbalance	• Investment in new reactive power compensation equipment (reactor or capacitor banks, static VAR compensator, synchronous condenser, etc.)	• Modify voltage set-points of the generating units and transformer's tap position • Switch on/off existing reactive power compensation equipment • VRE generation curtailment (mainly in low-voltage distribution networks)
	4b	• Presence of network overloads?		• Investment in network reinforcement (new lines, cables, transformers, etc.)	• Generation re-dispatch (including VRE curtailment) • Reactive power re-dispatch (in case overloads are created by high reactive power flows)
Short-circuit current computation	5a	• Violations of maximum short-circuit current level?	• Short-circuit currents at each busbar and circuit breaker • Assessment of minimum short-circuit levels to ensure protection co-ordination and selectivity	• New investments on network reinforcement (upgrading to a higher voltage level, short-circuit current limiters, etc.)	• Network topology switching (busbar split) • Generation re-dispatch (decrease amount of conventional generating units)
	5b	• Violations of minimum short-circuit current level?		• New investments in network reinforcement aimed at strengthening the network	• Generation re-dispatch (increase amount of conventional generating units)

Table 5: Description of elements for the technical studies flowchart (cont.)

Study		Evaluation criteria (C)	Main outputs (O)	Solutions (S)	
				Expansion planning	Operational planning
Transient stability analysis	6	• No generating unit is tripped due to the action of its protections (over-/under-speed relays, over-/under-voltage relays, low-voltage/high-voltage ride through (LVRT/HVRT) disconnection protection, etc.) • Voltage recovery criteria is met? • No machine loses synchronism • Critical clearing time (CCT) higher than the protection base time • No generating unit is tripped due to the action of its LVRT or HVRT protection	• List of secured incidents • Transient stability margin of the system (CCTs) • LVRT/HVRT characteristics of the system	• New investments on network reinforcement aimed at strengthening the network • Develop grid code requirements for LVRT/HVRT of generating units in case these requirements does not actually exist • Installation of out-of-step relays when CCT is lower than the stuck breaker and/or backup protection times	• Generation re-dispatch • Network topology switching • Implementation of special protection schemes • Installation of out-of-step relays when CCT is lower than the stuck breaker and/or backup protection times • Enforce that every new generating unit complies with LVRT/HVRT characteristics imposed by the grid code
Frequency stability analysis	7	• Correct actuation of UFLS schemes and primary reserves • Maximum transient frequency deviation lower than the first threshold of the UFLS scheme • Steady-state frequency deviation within the range specified in the operation criteria • Adequate activation of active power reduction schemes of VRE following over-frequency phenomena	• Adequacy of UFLS protection schemes • Adequacy of primary reserve levels (including the reserves provided by controlled load-shedding schemes)	• Increase frequency regulation capability of the system by requiring VRE sources to contribute to the primary reserve • Deployment of energy storage for frequency control purposes • Impose the implementation of virtual inertia function to the VRE power plants	• Improvement of UFLS schemes • Generation re-dispatch (additional conventional units dispatched at lower level to increase primary reserves and system inertia)
Voltage stability analysis	8	• No voltage collapse in part of or in the entire network • Steady-state voltage magnitudes within the range defined in the operation criteria	• Adequacy of reactive power/voltage control means	• Investment in network reinforcement (strengthen the network) • Investment in dynamic reactive power compensation means (static VAR compensator or synchronous condensers)	• Generation re-dispatch (additional conventional units dispatched at lower level or closer to the load centres to increase reactive power support) • Optimisation of the existing reactive power compensation means

BOX 4: CHALLENGE OF DATA AVAILABILITY TO PERFORM TECHNICAL STUDIES

An important challenge for performing VRE integration studies in SIDS is that there is generally a lack of suitable data to feed the mathematical models. This can be due to multiple reasons, including in particular:

- The absence or malfunctioning of monitoring devices on some equipment
- The absence of centralised monitoring and reporting procedures for system performance indicators
- A non-regular update of the available information
- Limited data exchange among different stakeholders
- Loss of data (paper or electronic) due to inadequate storage conditions or insufficient back-up.

Since the quality of the study results depends directly on the quality of input data, solving these issues is of prime importance for the planning process.

To compensate for a lack of local data, planning engineers can sometimes use publicly available sources and generic industry standards. However, it is important to validate the applicability of these data to local conditions before using them in study models.

Examples of generic data that can be found free of charge on the Internet are given below:

- Solar irradiation time series or solar PV generation profiles at nearby locations
    - *NREL's PV Watts Calculator* (NREL, n. d.)
- Availability, flexibility and fuel consumption parameters of thermal generators
    - *NREL 2010 – Cost and Performance Assumptions for Modelling Electricity Generation Technologies* (Tidball et al., 2010)
    - *World Bank 2013 – Operating and planning electricity grids with variable renewable generation: review of emerging lessons from selected operational experiences and desktop studies* (World Bank, 2013)
    - *World Bank 2011 – Caribbean regional electricity generation, interconnection, and fuels supply strategy* (Nexant and Hansen, n. d.)
    - *ECOFYS 2014 – Flexibility options in electricity systems* (Papaefthymiou et al., 2014)
    - Manufacturers' catalogues (not exhaustive)
        - *Wartsila 2016 – catalogue* (Wartsila, 2016)
        - *CAT – diesel generators catalogue* (CAT, n. d.)
        - *GE Power 2018 – gas power system catalogue* (GE Power, 2018)
- Standard dynamic regulation models of different types of generators (for exciters and governors)
    - *Neplan* (Neplan, n. d.)
    - *Siemens 2012 – Dynamic Models Package* (Siemens, 2012)
- Electrical parameters of network equipment (lines, transformers, etc.)
    - *Siemens – Power Engineering Guide Ed. 8* (Siemens, n. d.)

4. GENERATION ADEQUACY AND RESERVE SIZING TO ACCOMMODATE VARIABLE RENEWABLE ENERGY

This chapter is dedicated to two types of studies that ideally should be performed as part of generation capacity expansion plans (or master plans): generation adequacy studies and operating reserve sizing studies[20].

Both of these studies are related to the need to have sufficient generation capacity available to supply the load and to limit the risk of load shedding. Since reducing this risk to near-zero values would be prohibitive in terms of costs, these studies aim to ensure that an adequate amount of capacity and operating reserve is kept available in the system to reduce the risk to acceptable levels. This trade-off in the sizing of generation capacities or reserves is particularly relevant for SIDS due to the small number of generators in their power systems.

This chapter is intended to provide both a general overview and the methodology to perform generation adequacy studies and operating reserve sizing studies. Examples of study results are given to complement the theoretical information provided in this chapter, and further details of the methodology to perform generation adequacy studies and operating reserve sizing studies are outlined in Table 6 and Table 7.

4.1. Generation adequacy studies

In the context of this guide, the main technical challenge that generation adequacy studies address is the risk of having insufficient generation capacity available to supply all of the electricity demand in the presence of VRE. Due to the variable nature of renewable energy sources, adding VRE capacity in a system typically will lead to lower improvement of the generation adequacy than when adding conventional controllable generators of the same nominal capacity. The reason for this is the imperfect temporal correlation between the actual generation of VRE and the load. Nevertheless, increasing VRE installed capacity, keeping all other system characteristics unchanged, might improve generation adequacy.

To evaluate generation adequacy, reliability metrics (such as loss of load expectation, LOLE, discussed later in this section) have to be computed and then compared with the applicable criteria for the system. The use of probabilistic simulation software is generally required for this purpose. Two main types of inputs are needed to build an adequate model of the system for adequacy analysis: a forecast of the future load profile, and the statistical distribution of the availability of generating units.

Note that generation adequacy studies will not provide as an output a maximum level of VRE installed capacity, but rather will evaluate if a given generation expansion scenario, including VRE and possibly also dispatchable generators, will meet pre-defined reliability criteria.

If the criteria are not met, two possible solutions are:

- review the generation expansion scenario, or
- integrate other types of balancing capacities in the system (such as storage or demand response).

Such a feedback loop generally aims to find the least-cost solution to increase adequacy up to the required level.

Generation adequacy studies typically consider a time frame of one single year in the future for which the reliability is evaluated. These studies are relevant for long- to mid-term planning, when it is still possible to decide new investments in generation capacity. When considering investments in megawatt-scale generation infrastructures (or centralised storage) for SIDS, the time horizon for generation adequacy studies is typically two to five years ahead.[21]

20 Operating reserve sizing studies are also part of the operational planning studies, to determine the amount of reserves that actually should be committed.

21 Demand response or distributed storage capacities (*e.g.*, batteries) can be deployed in shorter time frames, as discussed in Chapter 9.

Study results and evaluation criteria

The most commonly used reliability criterion for generation adequacy is based on the probabilistic "loss of load expectation" metric. The LOLE is the amount of time during which it is statistically expected that the system load will exceed available generation, over a given time period. It is typically expressed in hours per year. The "expected energy not supplied" metric also is commonly used. The EENS is the average amount of energy that cannot be supplied to customers due to a lack of generating capacity, but should have been. It is typically expressed in megawatt-hours (MWh) per year.

Some deterministic criteria also are used for generation adequacy purposes, including:

- ***Largest unit contingency:*** this criterion is often used in small systems based on diesel generators to ensure that no service interruption would occur in case of unavailability of one or several generators (typically N-1, N-2 or N-3 criteria).
- ***Long-term reserve margin:*** this criterion imposes a fixed long-term reserve capacity margin above the peak load of the system (often expressed in percentage of the peak load). For example, it could be required that the total installed capacity is at least 20 % higher than the forecasted peak load.

However, such deterministic criteria are not well suited in the context of VRE integration given the higher variability of VRE power output compared to conventional controllable generators.

A generation adequacy criterion limiting the allowed LOLE value is applied in a large number of countries around the world. For developed countries belonging to large interconnected systems (*e. g.,* in Europe or in the US), targeted LOLE values are generally between 2.4 and 5 hours per year (2.4 hours per year corresponds to one day every 10 years).

Higher LOLE values are generally used in islanded or weakly interconnected systems and in developing countries for economic reasons (see explanation below). Examples of values used in SIDS power systems are 12 hours per year (Trinidad), 24 hours per year (Barbados) and 48 hours per year (Jamaica and Belize) (BLPC, 2014).

From an economic standpoint, the optimal LOLE level is reached when the value of lost load (VoLL, also referred to as *cost of unserved energy*) is equal to the cost of the additional long-term reserve capacity needed to reduce the amount of unserved energy. The VoLL is the economic value attributed by electricity consumers to the security of their electricity supply. Said differently, the point of equality between the two metrics above represents the point at which consumers are indifferent to either lost load, or the generation investment to prevent that loss of load.

In developed countries where a high share of the economy is dependent on reliable electricity supply, the system-wide VoLL is generally high (typically in the range of USD 10–50 per kilowatt-hour (kWh) lost). On the other hand, a lower VoLL is generally applicable to developing countries because of the lower dependence of their economies and normal activities on electricity. A USD 5 per kWh VoLL is, for example, used in Barbados (BLPC, 2014). VoLLs generally are obtained through surveys and statistical econometric modelling of the different consumer types (residential, commercial and industrial) for different time periods. The system-wide VoLL combines these different values in a single value applicable for the whole system, taking into account the relative weight of each customer type.

Methodology to perform the study

Carrying out such a study in systems with multiple generators requires the use of a probabilistic tool that is able to represent the stochastic nature of the problem. The two main components to represent in such tools (*i. e.,* to model) for generation adequacy studies are:

- the future load profile of the system over a chosen year (at hourly or quarter-hourly time steps), taking into account the uncertainty on the forecasted peak load, and

- the statistical behaviour of power generators' availability (conventional and renewable) over a given year, taking into account the statistical availability of underlying primary energy sources, forced outage probability and planned maintenance periods.

Historical measurements of the system load and of the availability of conventional generators are generally recorded by utilities and can be used to set up the core of the model. It is generally recommended to use historical measurements over long periods (at least 10 years, when available) to adequately integrate the probability of rare events (such as extreme meteorological conditions). The average availability of a generator is then the ratio between the number of hours during which that generator was available and the total number of hours during the observation period.

For new VRE generators, direct historical measurements of generated power output are generally not available. In this case, the best practise is to use historical measurements of the availability of the renewable energy source as close as possible to the site where future VRE generation will be located. Chronological time-series data on solar irradiation and wind speed, synchronised with the demand profile data, typically are used for this purpose. The correlation between VRE generation and load variations must be taken into account to correctly assess the system adequacy, which explains why using time-synchronised data is important. The time-series data on renewable energy sources are then converted to power units using the targeted installed capacity of VRE generators and their technical characteristics (*e. g.,* inverter efficiency for solar PV or wind turbine power curves for function of wind speed).

In the absence of detailed chronological data on renewable energy sources, non-chronological models can be used. In these models, the availability of renewable energy sources is represented through probability distributions (*e. g.,* Weibull law for wind speeds) that are independent of the load profile. The obtained reliability indices are less accurate in this case, but sometimes this is the only option when data are lacking.

Operating reserve requirements are typically needed as well, to ensure that sufficient generating capacity is available to supply load while keeping a margin to accommodate unforeseen power imbalances. The method to size these operating reserves is detailed in Section 4.2.

Based on the models and data described above, generation adequacy software tools will be able to estimate the LOLE of the system in the presence of VRE. Comparing this value with the targeted LOLE will indicate whether or not sufficient generation adequacy can be ensured in the system.

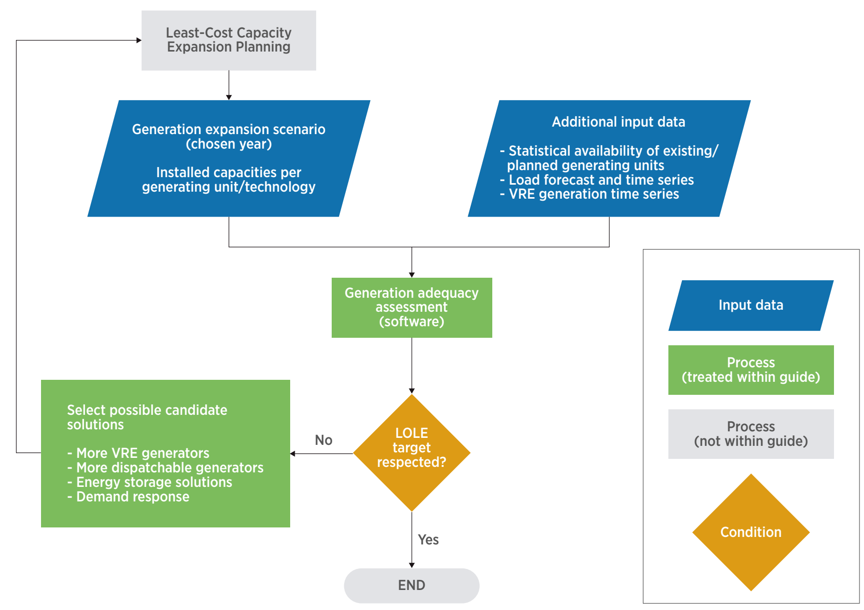
Dedicated generation adequacy software tools exist, but adequacy indices also can be obtained as a by-product of dispatch/production cost tools (described in the next chapter). However, the accurate assessment of adequacy indices necessitates the analysis of a large number of different cases, and dedicated adequacy software tools are usually preferred because they have a better numerical efficiency.

Table 6 summarises the main information required to perform a generation adequacy study to assess the LOLE in the presence of VRE.

Table 6: Summary of generation adequacy assessment

Requirement	Description
Model requirements	• Statistical representation of probability distributions for generators and load in the system. Convolution or Monte-Carlo methods are typically applied.
Input data	• Available capacity of existing/planned generators. • Forced outage rates, maintenance planning, temperature de-rating of generators, ideally based on historical measurements for existing units. • Load demand forecast for target year, historical and projected yearly load profiles with hourly or quarter-hourly time steps. • Statistical behaviour of local renewable energy sources availability based on historical measurements (solar irradiation, wind speed, hydro inflows) and related power output based on generator characteristics. Time synchronised measurements with the load profiles are desirable.
Methodology	• Choose one future year to model. • Model (*i. e.*, enter in software tool) the future load profile of the system over the chosen year (at hourly or quarter-hourly time step), taking into account the uncertainty on the forecasted peak load. • Model the statistical behaviour of power generators availability (conventional and renewable) over the chosen year, taking into account the statistical availability of underlying primary energy sources, forced outage probability and planned maintenance periods. • Compute reliability indices and compare them with targeted (or mandatory) values. • Adapt generation expansion plan if sufficient reliability is not ensured.
Scenarios	The same scenarios as the ones used in the generation expansion planning process can be used. Ideally, all future uncertainties must be treated in a probabilistic way to compute the future value of reliability indices. Scenarios can, however, be used to simplify the approach, for example by: • Modelling the target year first with mid-load demand forecast and then with high-load demand forecast (*e. g.*, 95th percentile) to represent the uncertainty in the peak load level (load growth, temperature dependency, etc.). • Modelling the target year first with average hydrological inflows and then considering exceptionally low inflows that could occur in a dry year for systems with hydroelectric plants.
Criteria for the analysis of results	• Targeted reliability indices of the system, typically LOLE in hours.
Outcomes of the simulation	• Reliability indices of the system (LOLE but also EENS). • Optional: optimal use of flexibility means (*e. g.*, storage assets) to increase reliability.
Interpretation of the simulation results	If the reliability criteria are not met under the generation expansion plan (including VRE), it means that the system does not have sufficient (or sufficiently reliable) capacity. Possible solutions include adding generation capacities, storage capacities or using demand response.
Examples of available software tools	ASSESS (RTE), CORAL (PSR Inc), PowerFactory (DIgSILENT GmbH), MARS (GE), MECORE (University of Saskatchewan and BC Hydro), PLEXOS (Energy Exemplar), PROMOD (ABB), REMARK (RSE), SCANNER (Tractebel), TRELSS (EPRI).

Figure 12: Workflow to perform generation adequacy studies



Analysis of results and next steps

If the computed LOLE is higher than the targeted one, it can be expected that the system will not have sufficient (or sufficiently reliable) capacity available. In such a case, a feedback loop with the generation expansion planning can be implemented to plan for more generation capacities or to integrate storage or demand-response capacities (discussed in Chapter 9). Building an interconnection with a neighbouring system also can be an option to increase reliability when it is technically and economically feasible. Data on the neighbouring power system are needed to evaluate such solutions.

Adding more VRE capacity will typically lead to lower improvement of the LOLE than adding conventional controllable generators. Because of the variability and lower availability of VRE, it has a lower effective load-carrying capacity (ELCC)[22] than conventional generators. The correlation of VRE generation profiles with the load profile is particularly important for this. If the peak load occurs at night, the ELCC value of a solar PV power plant is, for example, generally near to zero. On the contrary, if the VRE generation profiles are strongly and positively correlated with the load profile, the ELCC can be substantial (*i. e.,* above 50 %).

The contribution of VRE to adequacy also decreases at increasing penetration levels, especially when the VRE is based on a non-diversified mix of renewable energy sources (either in terms of primary energy source or in terms of geographical location) or when VRE generation does not coincide with the peak demand. Indeed, the ELCC of a new (or a marginal) VRE unit is linked to the correlation between its profile and the residual load profile. If a particular type of VRE unit is dominant at a specific location, the residual load profile will be negatively correlated to the generation profile of these VRE units. Consequently, the ELCC of an additional VRE unit of that type at that location will be low.

The potential revision of the generation expansion scenario implemented to solve adequacy issues will impact all of the other studies described in this guide. This explains why adequacy is generally the first topic that needs to be investigated.

22 ELCC represents the system load increase that can be accommodated when a new generator is added to the system while maintaining the same reliability level.

Workflow to perform the study

Figure 12 synthesises in a workflow how to carry out probabilistic generation adequacy studies. Note that probabilistic generation adequacy studies rely on a LOLE target, and such a target thus must be defined in the planning criteria.

Examples of study results

An example of results obtained from an adequacy study in Barbados is given in Figure 13. It shows how the addition of VRE capacities (everything else kept equal) would decrease the LOLE of the system. The lower marginal decrease at higher penetrations (saturation effect) is clearly visible (decreasing capacity credit[23]). No decommissioning of existing thermal units was assumed in the different VRE addition scenarios of the study. However, if VRE was used to replace the same amount of thermal capacity, the LOLE would increase (see blue dotted bar at top of Figure 13). In this case, a risk of not meeting the prevailing LOLE criteria (24 hours per year for Barbados) could exist.

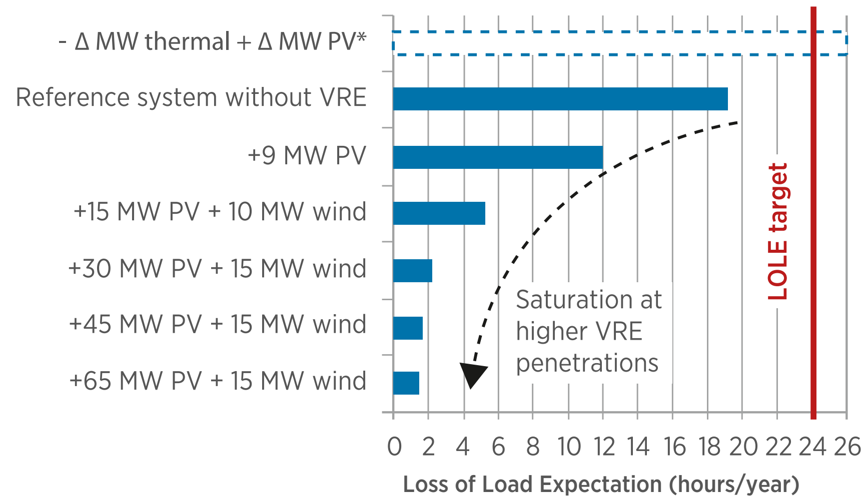
References for further reading

- Theoretical background on generation adequacy: Billinton and Allan (1996); IAEA (1984)
- Reports on the impact of VRE on generation adequacy: NERC (2011); Madrigal and Porter (2013)
- Evaluation of reliability criterion for an island (Barbados), taking into account VoLL: BLPC (2014).

4.2. Sizing of operating reserves

Operating reserves are active power capacities that are kept available on certain power generators (and possibly on storage assets and demand-response programmes) in order to accommodate unforeseen short-term variations in the behaviour of load and generation, and thus unforeseen imbalances between load and generation. Upward operating reserves aim to avoid power deficits, while downward operating reserves aim to avoid power surplus in order to maintain a stable system frequency.

Figure 13: Loss of load expectation for different wind/solar additions to the Barbados generation system.



Based on GE Energy Consulting, 2015.

23 The capacity credit of a generating unit is its contribution to reliably meet demand, measured in terms of either physical capacity (*e.g.*, MW) or the fraction of the generating unit's nameplate capacity (%).

In general, operating reserves can be broadly split into two categories (Madrigal and Porter, 2013; M.P.E. GmbH, 2013):

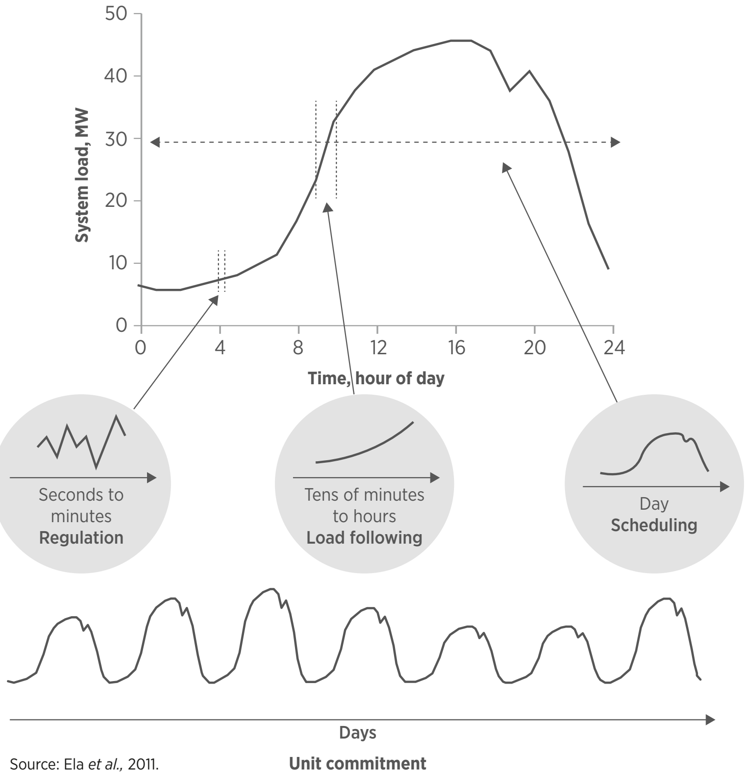
- ***Regulation reserves:*** These reserves compensate for the continuous real-time variations of load and generation and should be able to cover most of the possible contingencies in the system (unexpected outage of the largest generator, sudden load disconnection, etc.). They are activated automatically by grid-synchronised generators (or storage units) and cover timescales from several seconds up to 10–15 minutes. Primary reserve (deployed within a few seconds) and secondary reserve (deployed within several minutes) typically fall into this category.

- ***Load following reserves:*** These reserves compensate for the error between the scheduled and the actual generation due to uncertainties in load and generation levels. They cover periods ranging from 10–15 minutes to a few hours. Manual (or semi-manual) changes in generators' set-points can be applied for this purpose. Offline (or non-spinning) generators can also participate in these reserves. Tertiary and supplemental reserves typically fall into this category.

Note that different names and definitions for these reserves exist around the world, but the overall philosophy is always similar. The time frames of application for the reserves are illustrated in Figure 14 along with other longer time frames relevant for system operation.

In the context of SIDS, the definition of operating reserves is generally simpler than in larger, market-based systems, such as the North American or European systems. Frequently a single spinning reserve requirement aggregates both primary and secondary reserves (at second and minute timescales), and no load-following (or tertiary) reserve requirement is used. This is because utilities in SIDS do not often use operational planning processes for generation scheduling and load (and VRE) forecasting.

Figure 14: Power system operation time frames



Source: Ela *et al.*, 2011.

The main rationale behind this is that the diesel generators, present in most small-island generation fleets, are relatively flexible and can typically be started up by dispatchers within 10–15 minutes depending on the need identified.

The presence of VRE impacts the operating reserves for two main reasons:

1 If VRE generators are not designed to contribute to the operating reserve (*i. e.,* they often are designed to deliver the maximum energy available), displacing conventional generators by VRE generators reduces the capability to provide and deploy reserves.

2 The inherent variability and limited predictability of VRE sources might lead to higher needs for operating reserves in the system (in terms of size and/or frequency of activation).

This section focuses on the second aspect. The generation scheduling studies and stability studies described further in this guide address the first aspect by checking if the generation fleet (including VRE) is indeed capable of supplying the required operating reserve. Scheduling studies check if sufficient reserves can be available at every moment, while stability studies check if reserves can be deployed on time to respond to fast-occurring imbalances.

The need to maintain sufficient operating reserves in the presence of VRE can be related to both the intraday flexibility challenge and the frequency stability challenge discussed in Section 1.4 of this guide.

The sizing of operating reserves in the presence of VRE requires:

- The identification of contingency events that must be secured. If the system is operated in N-1 security, the contingency of the largest unit must be covered. Note that not all systems are operated in N-1 security.
- Performing statistical analyses of the variability and uncertainty on the net load[24]. Time-series data of load and VRE generation are the central inputs of these analyses. The main difference between this assessment and the adequacy assessment is that the focus here is on the possible changes occurring from one time step to the next (typically at sub-hourly timescales) rather than on the absolute level of load in comparison with available generation.

The reserve level is chosen to cover an acceptable risk for the system of not being able to accommodate such changes. The sizing of operating reserves does not directly impose a limit on the maximum VRE penetration. It is instead an input for generation scheduling and frequency stability studies. Note that it also can be viewed as an output of the planning process to guide real-time operation. For simple cases (*e. g.,* for very low or very high operating reserve sizes), it is possible to directly know, without additional study, whether or not the system will be able to provide sufficient operating reserves (*e. g.,* when the reserve is much lower or larger than the installed conventional capacity). As a general rule, however, proceeding with these additional studies is often needed.

Operating reserve sizing traditionally has been carried out as part of mid-term planning activities, with shorter time horizons than for generation adequacy studies (typically on a year-ahead basis). Historically the purpose of operating reserve sizing studies was not to influence the decision-making process for the construction of new generation capacities, but rather to estimate the appropriate amount of operating reserve to be kept within an existing generation fleet. There is generally a lower degree of uncertainty in the load forecast, in meteorological conditions, in installed generation capacities, etc. at this stage than at the stage of generation adequacy studies.

24 Net load variability was used by the US National Renewable Energy Laboratory in the Western Wind and Solar Integration Study (NREL, 2010).

When targeting high shares of VRE, operating reserve sizing can become both a long-term planning issue and a short-term operational planning issue.

- For the long term, the additional variability brought by VRE generators might require operating reserve levels (and flexibility capabilities) that might not be achievable with the foreseen generation expansion scenario. A review of this scenario could thus be needed.
- For short-term operational planning, it is generally more cost-efficient to update the reserve requirements based on the latest available information (such as VRE generation forecasts in day-ahead or in hour-ahead) than to impose a constant reserve requirement basis on worst cases.

Study results and evaluation criteria

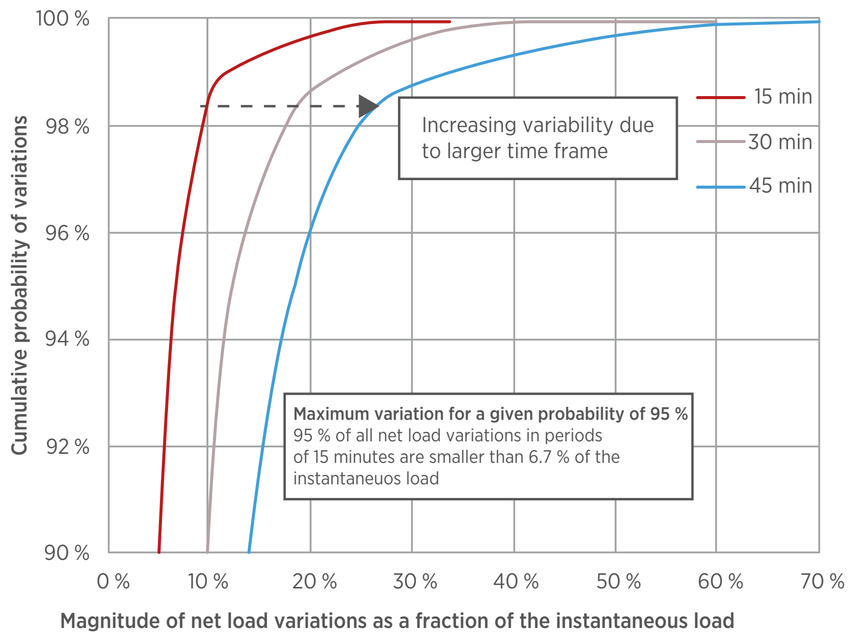
The output of operating reserve sizing studies is the level of operating reserve required (in MW) at a future point in time and covering a certain degree of risk.

A typical criterion used is that the operating reserves should be able to accommodate net load variability under a certain probability (*i. e.,* for a certain percentage of the time). Probabilities between 95 % and 99.99 % are typically used, and the required reserve is computed as the associated percentile in the probability distribution of the net load variation.

Metrics based on standard deviations (σ) of net load variations are also commonly used (*e. g.,* the US National Renewable Energy Laboratory's *Western Wind and Solar Integration Study* made use of three times the standard deviation of 10-minute net load variation). However, it is recommended to use percentiles given that VRE variations usually do not follow a normal probability distribution function.

Setting a probability for the acceptable risk involves a trade-off between system security and the operating costs associated with keeping operating reserves online. The chosen threshold can, if needed, be adapted in an iterative way based on the cost outputs of generation scheduling studies.

Figure 15: Illustrative cumulative distribution function of VRE output variations.



The different curves represent different ensembles of PV systems.

For SIDS, the operating reserve sizing studies can generally focus on regulation reserves, considering a time frame of 10–15 minutes. This is motivated by 1) the definition of operating reserves in SIDS (and the absence of load-following reserves) and 2) by the fact that the probability of experiencing large VRE output variations increases with the length of the time interval considered (for example, larger variations can be expected over 15 minutes than over 1 minute, as shown by Golnas *et al.* (2012)).

The cumulative distribution functions presented in Figure 15 illustrate the second point above. Such curves make it possible to determine the maximum step change that can be expected from the net load of a system with a certain probability.

The capability of the system to accommodate VRE variations in time intervals larger than 10–15 minutes (*i. e.,* larger than the time interval covered by small-island regulation reserves) will be treated as part of the generation scheduling assessment described in the following chapter.

Methodology to perform the study

The recommended methodology for sizing operating reserves in the presence of VRE involves a statistical analysis of the possible net load variations, *i. e.,* variations in the load minus the forecasted output of the different VRE generators, at a 10- or 15-minute timescale in the system. The goal is to produce cumulative distribution functions, such as the ones in Figure 15, for the net load variations as function of the instantaneous load for a given VRE integration scenario. The selection of a threshold percentile for acceptable variations results in the percentage of instantaneous load to be provided as operating reserves. As an example, Figure 15 shows that 95 % of the net load variations (in periods of 15 minutes) could be covered with 6.7 % of the instantaneous load. The absolute value in MW of the operating reserves can then be calculated using the latest load forecasts available.

As for adequacy studies, synchronous time series of historical load profiles and VRE generation are required for such statistical assessment. The resolution of these time series should match the chosen timescale (10 or 15 minutes). If measurements are not available at that timescale, data collection mechanisms must be improved to have an appropriate sizing of the reserves.

In addition to the risks related to intrinsic load and VRE variations, the regulating reserves also should be able to cover the loss of the largest generating unit[25] and of the largest load disconnection (single largest contingencies) in the system. Note that when an important capacity of VRE is connected to the grid through a single transmission element (*e. g.,* line or transformer), the loss of generation due to that outage also must be covered.

Different approaches can be followed to aggregate in a single value the contingency reserve requirement and the requirement for net load variations:

- A conservative approach consists in summing the operating reserve required for contingency and for net load variation in order to be able to accommodate a simultaneous occurrence of both risks.

- An optimistic approach would be to consider, on the other hand, that both risks are relatively independent and that taking the maximum between the two values as required operating reserve would be sufficient. This is done in the Canary Islands, for example (Sigrist *et al.*, 2016).

- A more advanced (and effort-consuming) approach is to compute the actual probability of simultaneous occurrences of both risks. This is rarely applied in practice.

The choice of a specific approach is motivated by the economic trade-off between the operating costs and the

25 In some SIDS systems such a requirement is not imposed due to economic considerations. The use of UFLS schemed is then needed to complement operating reserves in case of loss of the largest generating unit.

economic impact of load shedding. When the amount of reserves increases, the operating costs increase while the risk of load shedding decreases.

It is recommended to take into account the particularity of some time periods when sizing the operating reserve. For example, there is no variability in solar PV output during night time, and the statistical analysis discussed in this section can thus be performed separately for day and night periods, possibly yielding two different operating reserve requirements for these periods.

Table 7 provides a summary of the methodology for assessment of operating reserve sizing.

Table 7: Summary of operating reserve sizing assessment

Requirement	Description
Model requirements	• Standard statistical analysis models.
Input data	• Available capacity of existing/planned VRE generators. • Load demand forecast for target year, historical and projected yearly load profiles with 10- to 15-minute time steps. • Time series of the availability of local renewable energy sources based on historical measurements (solar irradiation, wind speed, hydro inflows) and related power output based on generator characteristics. Time-synchronised measurements with the load profiles are desirable.
Methodology	• Choose one future year to model. • Compute the future net load profile based on historical time series of the net load (scaled to the forecast peak demand) and of synchronised time series of expected VRE outputs (based on solar irradiation, wind speeds, etc.). A 10- or 15-minute time resolution is recommended. • Compute cumulative distribution curve of net load variations over the instantaneous demand and choose a threshold percentile for acceptable net load variations (typically from 95% to 99.99%). If relevant, use different curves for different time periods (*e.g.*, daytime and night time in presence of solar PV) • Integrate risk of single largest contingencies (upward or downward): ◦ Conservative: sum the operating reserve required for contingency and for net load variations ◦ Optimistic: take maximum between the two values.
Scenarios	The same scenarios as those used in the generation expansion planning process can be used (*e.g.*, if different VRE integration scenarios are analysed).
Criteria for the analysis of results	• Optional: cost of maintaining the computed reserve level available can be assessed with generation scheduling studies. Feedback loop possible on chosen percentile threshold if costs are too high.
Outcomes of the simulation	• New operational practice regarding operating reserves. • Required level of operating reserves to be used in generation scheduling studies. • VRE output variation event(s) for frequency stability studies.
Interpretation of the simulation results	Computed level of required operating reserve with and without VRE integration can be compared to assess the VRE impact on reserve sizing.
Examples of available software tools	Excel (Microsoft), Matlab (Mathworks), R, Python, or any other statistical analysis tool.

Analysis of results and next steps

The operating reserve studies described in this section generally will not result directly in a particular limitation for VRE penetration at the long-term planning stage (*i. e.,* when evaluating future VRE integration scenarios). The obtained results have to be integrated in generation scheduling studies and frequency stability studies to assess the technical feasibility of maintaining or providing these reserves in practice. Eventually the objective is to use the computed operating reserve requirement for the operation of the system.

The required level of operating reserves (in MW) is a direct input for generation scheduling studies. For stability studies, the statistical analysis performed for operating reserve sizing generally helps in defining the constraints while simulating events related to sudden variations in VRE output.

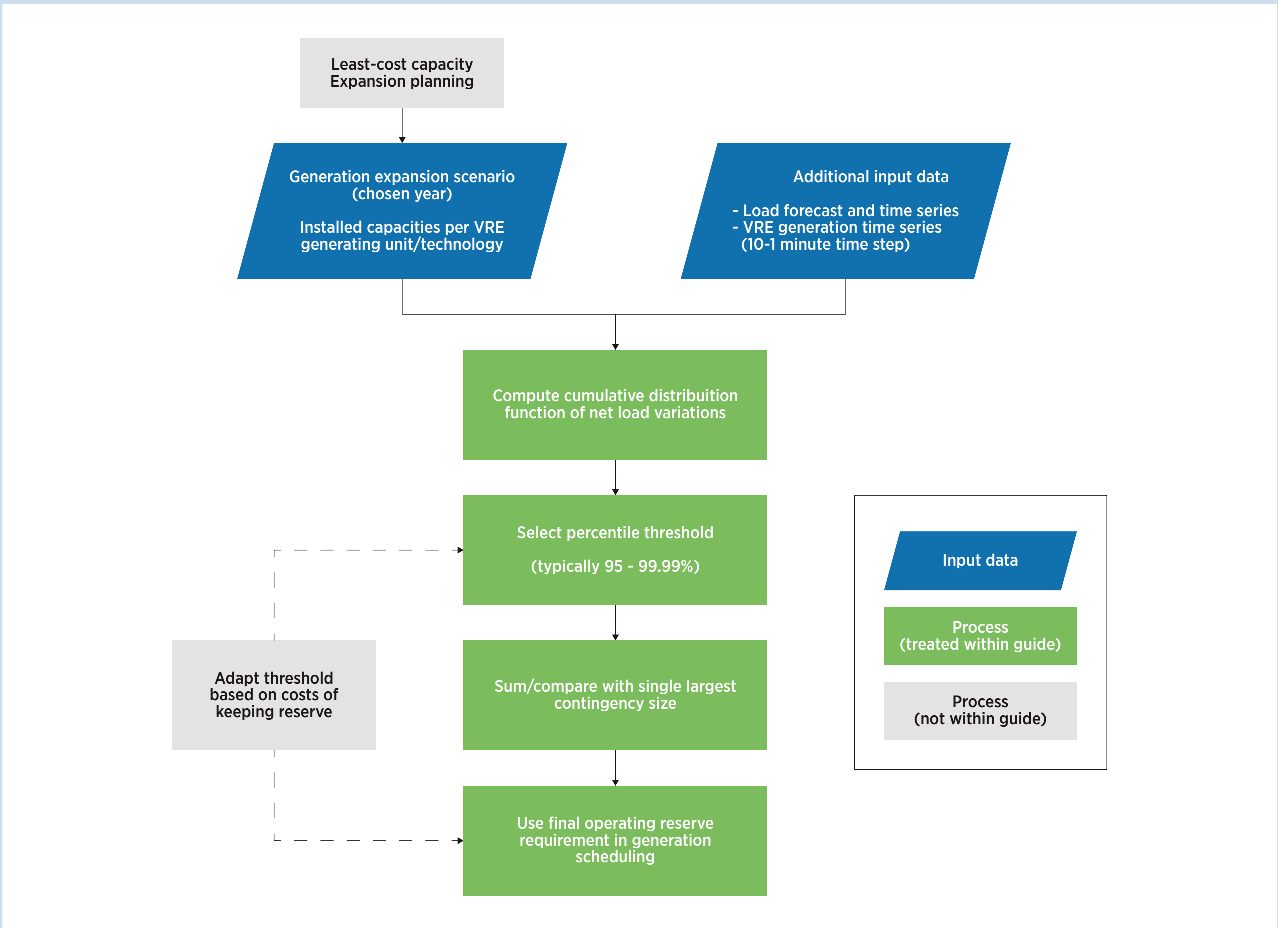
For example, extreme variations of the VRE outputs covering 99.97 % of all possible variations can be chosen.

In some simple cases, the planner will already be able to know, without additional study, whether the system will be able to provide the computed operating reserves or not. For example, this would be the case if the required reserve is higher than the capacity of assets that can technically provide reserves. Even in such a case, conducting generation scheduling and frequency stability studies would still be interesting in order to determine to what extent operating reserves are lacking.

Workflow to perform the study

Figure 16 synthesises in a workflow how to proceed with operating reserve sizing in the presence of VRE.

Figure 16: Workflow to perform operating reserve sizing



Examples of study results

Figure 17 presents outputs from another operating reserve sizing study: the comprehensive Hawaii Solar Integration Study (Eber and Corbus, 2013), which considered different scenarios of VRE development. A 99.99 % probability of meeting VRE variations was used as the threshold for operating reserve sizing in this study. The required reserves are differentiated for daytime and night time, and they depend on the amount of forecasted VRE generation.

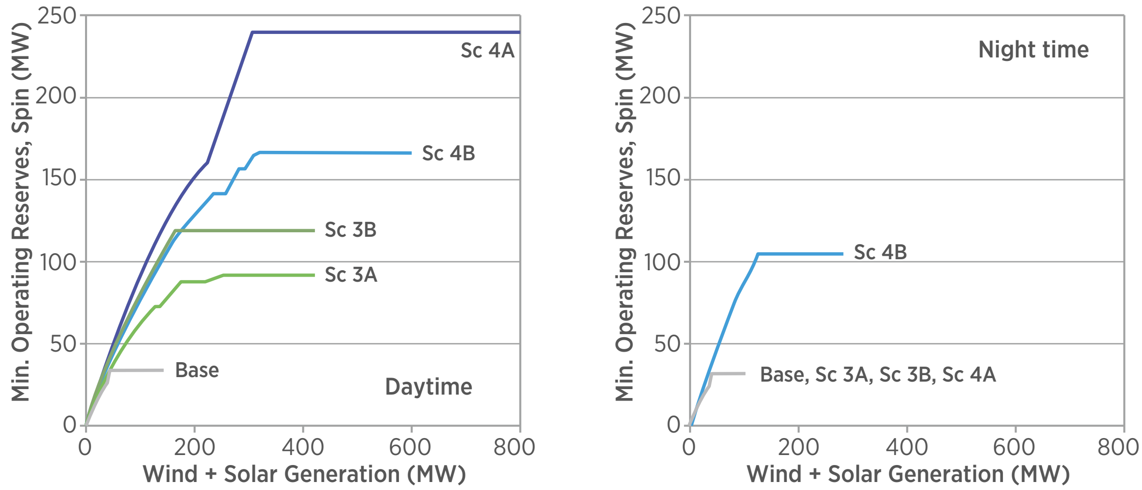
References for further reading

For more detailed information on operating reserve sizing, see the following references:

- Reports discussing the impact of VRE on operating reserves and comparing results from several studies: Ela *et al.* (2011); Madrigal and Porter (2013)

- VRE integration studies in islands (Barbados, Hawaii and Seychelles), tackling inter alia the sizing of operating reserves: Eber and Corbus (2013); GE Energy Consulting (2015); Brown et al. (2016).

Figure 17: Upward operating reserve requirement for different VRE integration scenarios in Oahu island, Hawaii



Scenario	Distributed PV	Central Plant PV	On-Island Wind	Off-Island Wind	Total
Baseline	60 MW	-	100 MW	-	160 MW
3A	260 MW	100 MW	100 MW	-	460 MW
3B	160 MW	200 MW	100 MW	-	460 MW
4A	360 MW	400 MW	100 MW	-	860 MW
4B	160 MW	200 MW	100 MW	200 MW	660 MW

Source: Eber and Corbus, 2013.

5. GENERATION SCHEDULING AMID GROWING SHARES OF VARIABLE RENEWABLE ENERGY

Once the generation adequacy is assessed, the power system in the presence of VRE is evaluated by means of generation scheduling studies. Such studies are essentially related to the flexibility challenge of accommodating intraday variations of load and generation in the presence of VRE.

These studies are generally carried out with unit commitment and economic dispatch (UCED) software tools. Such tools make it possible to optimise the power outputs of the different dispatchable generators in order to meet a given load forecast (or net load forecast in the presence of VRE). Unit commitment refers to the selection of generation units that should be online at a given time, while economic dispatch optimises the amount of power produced by each unit in order to meet demand while minimising operational costs. In other words, the UCED optimisation problem is mathematically expressed in terms of an objective function subject to constraints. The objective is typically to minimise the operational costs, while the constraints are linked to the power system and to the technical characteristics of power plants. An essential power system constraint is that generation and demand should be in balance at each time step.

This chapter aims to present both a general overview of and the methodology to perform a generation scheduling study in view of accommodating increasing levels of VRE in small-island power systems.

Current practice in generation scheduling

The main purpose of using UCED software in view of VRE integration is two-fold:

1 The generation fleet should be sufficiently flexible to cover slower variations in the net load than those covered by operating reserves (*i.e.,* from 10–15 minutes to several hours). These slower variations allow actions such as the scheduling of generators, while faster variations do not provide enough time for this, having to be covered by the operating reserves.

2 All technical constraints should be met including the operating reserves, the technical minimum of generators, the ramping limits, greenhouse gas emission limits, etc.

As a basic result from the UCED model, the power produced by each generator at each time step is calculated. This provides a first indication on how the power system should be operated. An example output of the generation scheduling per technology for a day with high VRE penetration is provided in Figure 18.

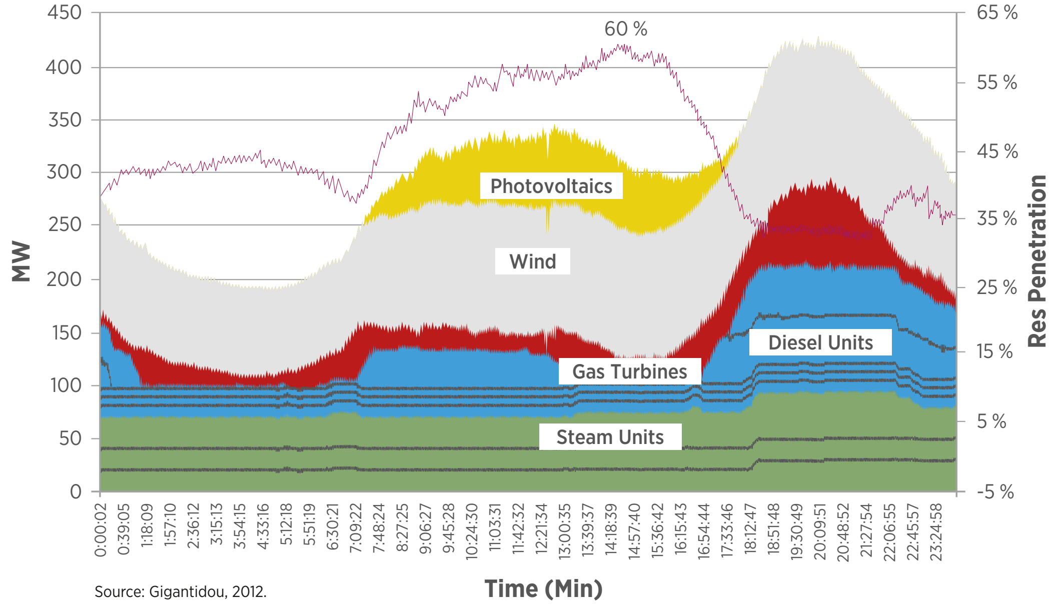
Apart from the generation dispatch, three main output indicators can be distinguished:

- feasibility of the generation schedule in the presence of VRE,
- amount of VRE curtailment needed to satisfy all technical constraints, and
- grid congestion and its impact on the level of generation operating costs.

Besides the knowledge of VRE and load forecast time series, generation scheduling studies also require as an input a precise description of all operational constraints that apply to each dispatchable generator and its flexibility capabilities.

Occasionally a simplified network representation is included in the UCED software. This makes it possible to account for network congestions before more detailed network studies are performed. It should be noted that an increased share of VRE requires a more detailed network representation. Specific network studies are highlighted in Chapter 6.

Figure 18: Generation mix for Crete's power system on 5 March 2013 and renewables penetration (violet line)



Source: Gigantidou, 2012.

In the context of SIDS, conventional generation is often based on diesel generators that can be started and ramped up or down relatively quickly. Flexibility is therefore less of a problem in such diesel-based systems than in larger systems in which inflexible gas or steam turbines are present. However, with increasing VRE penetration, flexibility challenges could also arise in SIDS.

Generation scheduling studies can be used in several ways in view of VRE integration:

- They can be used as part of the operational planning phase and carried out on a day-ahead (or week-ahead) basis in order to perform the actual generation scheduling of the system based on the latest available forecast of load and VRE generation. This makes it possible, for example, to identify periods in which VRE curtailment could be needed.
- They also can be used as part of the mid- or even long-term planning stages since the flexibility needs can influence the choice made within the capacity expansion planning phase. Note that the flexibility needs can be fulfilled by the supply and demand side. With generation scheduling studies it is possible to:
  - Find the maximum VRE installed capacity that can be accommodated without any flexibility issue.
  - For more ambitious VRE deployment scenarios, assess the depth and frequency of occurrence of operational issues that could arise due to insufficient flexibility. A feedback loop with the capacity expansion planning can then be implemented to solve the identified issues by adding flexibility in the system.
- They make it possible to detect the critical scenarios that deserve further analysis by means of detailed network studies (see Chapter 6).

In addition to the uses listed above, generation scheduling studies can provide useful information on the impact of VRE integration in small-island power systems, including:

- the impact of VRE integration on generation operational costs:
  - decrease in operating costs due to displacement of thermal generation by VRE sources,
  - increase in operating costs due to more frequent operation of thermal generators at part load and higher cycling of units (modulation and start-up/shut-down manoeuvres),
  - variation in operating costs due to the required reserve provision;
- the impact of VRE integration on pollutant emissions (*e.g.,* carbon dioxide).

Study results and evaluation criteria

The feasibility or infeasibility of the UCED optimisation is the main criterion that makes it possible to assess whether the initially planned VRE generation is technically achievable or not. Infeasibility implies that no solution can be found that satisfies all operational constraints. Therefore, the planned integration of VRE should be reassessed.

Even if the UCED problem is feasible, some additional indicators should be assessed to evaluate the impact of VRE integration. The first is the amount of VRE generation curtailment that would be needed to satisfy all operational constraints. For example, curtailing some VRE generators might be needed to maintain sufficient downward or upward operating reserves available at times of high VRE power output and low load (*i. e.,* high instantaneous VRE penetration). Model outputs for operating cost and pollutant emissions also can be considered as criteria for triggering the need to investigate additional flexibility options. For example, frequent operation of conventional generators at part load could make it possible to reach a given VRE target but could lead to unacceptable increases in fuel consumption, operating costs or pollutant emissions.

Given the diversity of possible situations, no standardised threshold values exist for the acceptable levels of VRE curtailment or generation operation costs. These are generally left to the appreciation of the planner, based on his or her expert judgement and knowledge of the local context (see Chapter 2).

In case of infeasibility of the UCED problem, it is common practice to relax some constraints of the problem to be able to identify the constraining periods and the nature of potential issues. Such relaxations might be applied to allow violation of operating reserve requirements or load-shedding activation (energy demand that is not served, usually with a penalty cost). The frequency or depth of activation of these measures in the simulation outputs can then be judged as acceptable or not, depending on the particular context of a given small island developing state.

Methodology to perform the study

The available software tools target different levels of detail and complexity; thus the choice of the tool should be aligned with the required detail of the study.

When used for long-/mid-term planning of VRE integration, such studies should ideally be performed for a full year at sub-hourly time steps (*e. g.,* 10 or 15 minutes), considering the possible load and VRE output variations based on historical measurements. State-of-the-art UCED tools are typically capable of handling large time horizons (up to a few years) with reasonable computation times provided that the number of controllable generators is not too high (which is generally the case for SIDS).

Another option, if computation time becomes an issue, is to select typical days or weeks that are expected to be the most constraining in terms of net load variations (at 10–15 minute time steps), rather than modelling full years. The days with the highest net load ramping (*e. g.,* during morning load pick-up or evening nightfall) or with low load and high VRE penetration are typically the ones during which flexibility issues can be expected. Again, the experience of the planners and their understanding of the local system are key to identifying these events (see Chapter 2). Modelling the occurrence of sudden meteorological events such as storms, inducing important decreases in VRE outputs, is also relevant for small-island systems.

Besides load and VRE variation patterns, generation scheduling and dispatch studies also must represent the technical flexibility constraints of the controllable generation units. The main parameters needed for each generator are the following:

- ***Technical minimum:*** % of nameplate capacity below which the generator cannot be operated (except during start-up/shutdown phases).
- ***Minimum up time:*** minimum amount of time during which a generator must remain in operation after having been started up.

- ***Minimum down time:*** minimum amount of time during which a generator must remain offline after having been shut down.

- ***Start-up time:*** time required to bring a generator online. Depending on definitions it can refer to the time required to reach the technical minimum or the nameplate capacity. This time is usually shorter when the generator is already warm or hot (if the unit has not cooled down since last usage or if pre-heating is applied).

- ***Maximum ramp up/down rate:*** the maximum increase/decrease in power output over a period of time (usually in MW per minute or % of nameplate capacity per minute).

- ***Maximum reserve contribution:*** the maximum contribution of the generator to operating reserves (in MW or % of nameplate capacity). This depends on maximum ramp rates and/or droop characteristics of the generator governor (depending on the time frame covered by operating reserves).

- ***Must-run status:*** if the generator has to be kept online and cannot be shut down (except for maintenance purposes). This can, for example, be the case for co-generation plants supplying steam to an associated industrial process, if the generator is needed for voltage control on the network, or if a maximum number of start-ups is defined for the generator.

The values of these different parameters can generally be obtained in the documentation provided by generator manufacturers (*e. g.,* in datasheets). If some information is missing, generic industry standards can be used. Typical flexibility characteristics of the main types of controllable generators are provided in Table 8. Model inputs such as heat-rate curves (showing how fuel consumption is impacted by the output power level) or start-up costs are also required when cost estimations are expected. Sometimes, the model parameters can follow from contractual agreements with IPPs as defined in the PPAs. In this case, the constraints are no longer linked to the generators themselves, but rather to the operation of the power system. Again, for such constraints the experience and understanding of the planner are essential (see Chapter 2).

The actual capabilities of the control means available to modulate the output of generators in the system (*e. g.,* automatic generation control, remote curtailment of VRE, etc.) should also be considered in order to avoid computing purely theoretical flexibility capabilities of the generation system. Depending on the software tool, such additional parameters can be included.

Table 8: Flexibility characteristics of controllable generators

Name	Technical minimum (%)	Ramping rate (%/min)	Start-up time (hours)	
			Cold	Hot
Diesel generator	30–50	10–100	< 0.25	< 0.1
Open-cycle gas turbine	20–50	5–20	0.25–1	0.1–0.25
Combined-cycle gas turbine	15–50	2–10	2–6	0.5–2
Coal-fired steam turbine	25–45	1–6	4–16	1–3
Water turbine (hydropower)	< 15	40–100	< 0.1	< 0.1

Source: EURELECTRIC, 2011; Madrigal and Porter, 2013; Papaefthymiou et al., 2014.

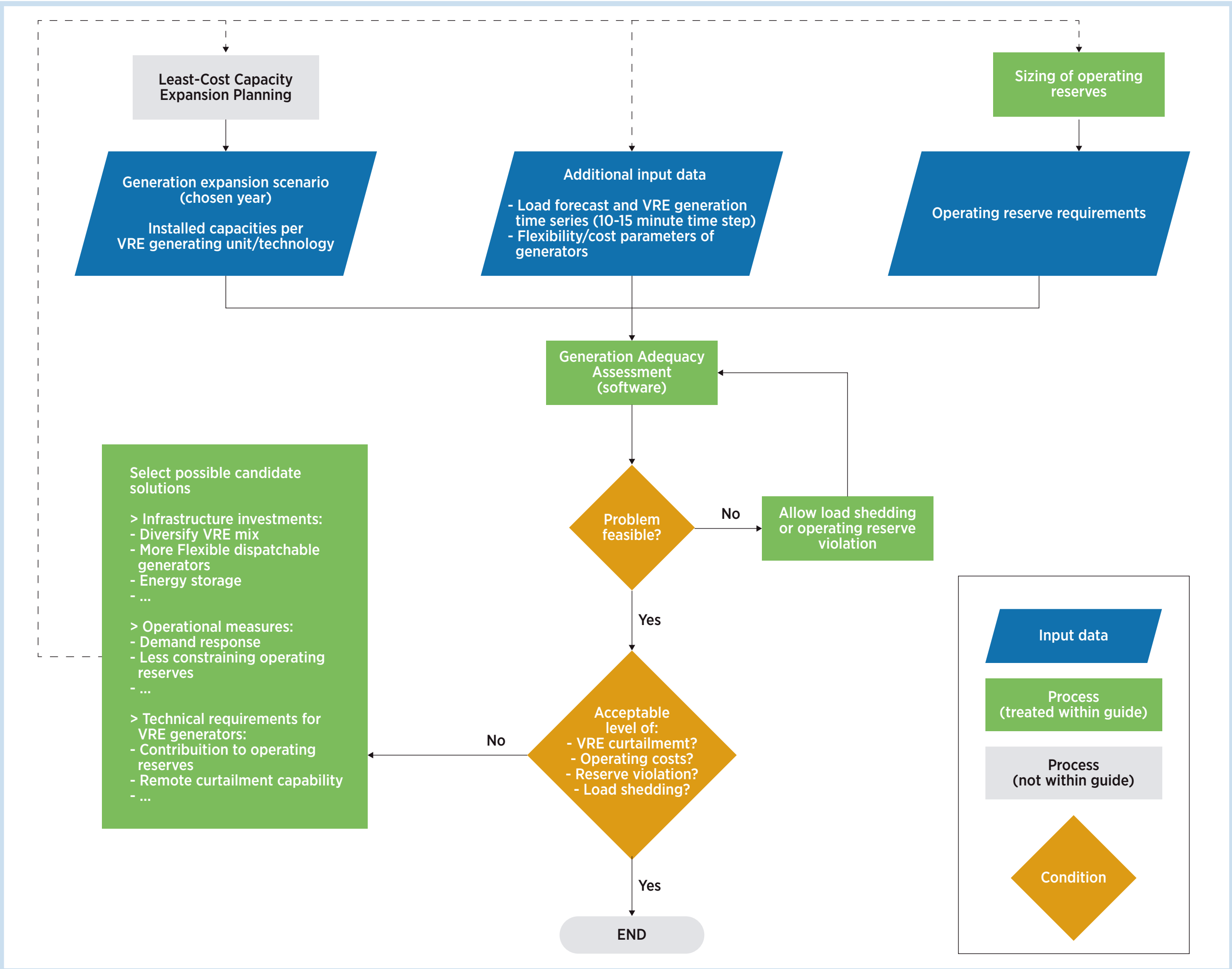
Analysis of results and next steps

The analysis of results can be done through the following questions:

- Is the UCED optimisation feasible? In other words, can all technical constraints on dispatchable generators and the required level of operating reserves be met by the optimisation?
- If the problem is feasible, do the following indicators reach acceptable levels as to the understanding of the planner (see Chapter 2)?
  - operational generation costs
  - amount of curtailed VRE generation, instantaneous or average (year, week, day).
- If the problem is infeasible, the same questions as above apply, and the frequency/depth of the following events also should be assessed:
  - Violation of operating reserve constraints
  - Need to apply load shedding.

At the long-/mid-term planning stage, numerous solutions exist to add flexibility to the system if the indicators listed above are not at acceptable levels. They include infrastructure investments (*e. g.,* storage or flexible thermal/hydro generation), operational measures (*e. g.,* demand response or review of operating reserve requirements) and technical requirements for VRE generators (*e. g.,* contribution to operating reserves or remote curtailment capability). The different possible options are discussed in Chapter 9.

Figure 19: Workflow to perform generation scheduling studies



At the operational planning stage, generally there is almost no choice than to accept that the system will have to be operated in a sub-optimal mode if the above indicators are not satisfied. This could mean operating the system at high operating costs, with high VRE curtailment, with a shortage of operating reserve or with some load shedding. Often additional real-time actions will be required.

Workflow to perform the study

Figure 19 synthesises in a workflow how to proceed with generation scheduling studies.

The study starts from three main inputs. The first input results from a selected year from a generation expansion planning scenario. Here, the corresponding installed capacities per generator or technology are integrated in the generation scheduling software. Second, additional input data such as the load and VRE time series and detailed techno-economic characteristics of power plants are collected. Finally, the operating reserve requirements, as discussed in Section 3.1, are integrated in the generation scheduling software.

Once the input data are inserted in the software, the optimisation can be launched. The result will indicate whether the model is feasible or not. If the model is infeasible, a typical adjustment is to allow for load shedding or operating reserve violation. This could help in reaching a feasible outcome of the optimisation that can be further assessed.

The planner assesses the acceptability of a feasible solution by analysing parameters such as the curtailment of VRE and the level of operational costs. If the results are not deemed acceptable, several candidate solutions can be implemented, after which the generation scheduling optimisation is re-run. As described in Chapter 2, understanding the underlying power system and the interaction with VRE are essential at this stage.

Examples of study results

Examples of generation scheduling studies include the following:

- Brown et al. (2016) provide results on how different flexibility solutions make it possible to increase solar PV penetration while meeting the required operating reserves. In this study, performed for the main island of Mahé in the Seychelles, the reserve requirement was based on the assumption that 80% of the solar PV generation could be lost in 10 minutes. A summary of results considered for 2030 is given in Table 9 .
- VRE integration studies in islands (Barbados, Hawaii and Seychelles) tackling, inter alia, generation scheduling issues: Eber and Corbus (2013); GE Energy Consulting, 2015; Brown et al. (2016).

Table 10 summarises the main information required to perform generation scheduling studies.

References for further reading

For more detailed information about generation scheduling studies, see the following references:

- Textbook on the operation and control of power generation: Wood et al. (2013).

Table 9: Solar PV integration limits due to flexibility constraints in 2030 scenarios for Mahé island in Seychelles

Scenario	PV [MW]
Base Case (BC) (65% min. generator loading, no extra technology)	29.1
BC + 7 MW of Demand-Side Management (customers can decrease/increase their load within 5 minutes to support PUC's power balancing)	34.3
BC + 7 MW of storage (such as batteries and/or pumped hydro storage)	34.3
BC + Limit PV inverters to 80% of PV panel size (reduces PV peaks with tiny effect on energy production)	36.4
BC + Curtailment of large units during bottlenecks (only when simultaneously feed-in is high and load is low)	38.8
BC + Keep a 15 MW backup generator on standby (so it can start up in a shorter period, *e.g.* 5 minutes)	39.5
Conservative scenario (75% min. loading, no changes to existing system)	21.5
Moderate scenario (65% min. loading, DSM, 80% inverter limit, curtailment)	57.2
Advanced scenario (50% min. loading, DSM, 80% inverter limit, curtailment, standby generator)	85.8

Source: Brown et al., 2016

Table 10: Summary of generation scheduling studies

Requirement	Description
Model requirements	• Unit commitment and economic dispatch (UCED) tool. Note: stochastic UCED tools, optimising the generation schedule in order to be robust to multiple possible levels of VRE generation (taking into account possible forecast errors) are the state of the art. However, deterministic UCED (only considering a single VRE output realisation) can already provide satisfactory results in most cases.
Input data	• Available capacity of existing/planned generators. • Load demand forecast for target year, historical and projected yearly load profiles with 10–15 minute time steps. • Time series of the availability of local renewable energy sources based on historical measurements (solar irradiation, wind speed, hydro inflows) and related power output based on generator characteristics. Time-synchronised measurements with the load profiles are desirable. • Technical (or contractual) flexibility characteristics of controllable generation units: technical minimum, minimum up/down time, start-up time, ramping limits, maximum reserve contribution, must-run constraints, etc. • Optionally: generators' cost parameters (*e.g.*, heat-rate curves and start-up costs). • Operating reserve requirements (from operating reserve sizing study).

Table 10: Summary of generation scheduling studies (cont.)

Methodology	• Choose one future year to model. • Model (*i. e.*, introduce in UCED software) the future chronological load profile and time-synchronised VRE generation profiles over the chosen year or in selected constraining days/weeks based on historical time series (scaled to the future forecasted peak demand). A 10–15 minute time resolution is recommended, but hourly time steps can be used if data are lacking. • Model the technical flexibility constraints of the controllable generators in the system (and optionally their economic and fuel consumption characteristics). • Integrate operating reserve requirements (possibly depending on time of day). • Run UCED tool over the chosen time frame. • Apply relaxations in case of infeasibilities (*e. g.*, allowed violation of operating reserve requirement, or allowed load shedding). • Assess if frequency/depth of following indicators is acceptable: VRE curtailment, high operational generation costs, violation of operating reserve requirements, load shedding activation. If not acceptable, implement flexibility options in the system.
Scenarios	• The same scenarios as those used in the generation expansion planning process can be used (*e. g.*, if different VRE integration scenarios are analysed). • Modelling of full years is convenient since it avoids the need to pre-select constraining days/weeks for the assessment. If computation time is an issue (*e. g.*, with a large number of generators), it is recommended to assess at least the following situations: ◦ days in which highest net load ramping are expected ◦ days with minimum load and maximum VRE penetration ◦ days with maximum load and maximum VRE penetration ◦ both dry and wet seasons should be modelled for systems with hydropower.
Criteria for the analysis of results	• Feasibility/infeasibility of the UCED problem. • Acceptable levels for the following indicators: VRE curtailment, operational generation costs, violation of operating reserve requirements, load shedding activation
Outcomes of the simulation	• All metrics mentioned in above criteria. • Optimised scheduling of controllable generators.
Interpretation of the simulation results	Flexibility options must be investigated if criteria are not met.
Examples of available software tools	ANTARES (RTE), HOMER (Homer Energy), jROS (Siemens), MAPS (GE), PLEXOS (Energy Exemplar), PROMOD IV (ABB), SDDP/NCP (PSR Inc).

6. NETWORK STUDIES FOR SYSTEM PLANNING IN SMALL ISLAND DEVELOPING STATES: STATIC STUDIES

This chapter presents an overview of the static network studies in view of accommodating increasing levels of VRE in SIDS power systems. The three different types of simulations performed for this category of studies are:

- load flow (normal operating conditions)
- static security assessment (contingency analysis)
- short-circuit currents.

The static studies are related to the analysis of a power system in a steady-state condition (*i. e.,* for a specific point in time and the associated state of the system without changes in load or generation).

In static studies, any transients resulting from disturbances are assumed to have settled down and the system state is unchanging in time. Specifically, system load, including network losses, and power generation are exactly matched. Under such condition, all system variables are constant.

To investigate the steady-state operating condition of a power system, the following is verified (Glover et al., 2011):

- Generation supplies load (demand) and network losses.
- Bus voltage magnitudes are within a range close to rated values.
- Generators operate within their capability limits (active and reactive power).
- Network branches (lines, cables and transformers) are not overloaded.

The main types of studies performed for the analysis of a power system in a steady-state condition are presented in the following sections.

6.1. Load flow

The load flow[26] study is essential for analysing network adequacy from the point of view of steady-state operation. This study aims to determine the voltages and power flows across the entire network in normal operating conditions (*i. e.,* when no contingency is observed in the network, such as the loss of one branch or of one generator). It is a standard study that should be carried out for any type of small-island power system, without any distinction in the generation mix and VRE penetration level.

The deployment of VRE sources demands specific analyses due to the variable and stochastic nature of these sources, their location (sometimes far from load centres) and their specific capability to provide voltage/reactive power control. Furthermore, as VRE generation varies much more than the production of non-VRE in pure thermal power systems, additional scenarios for load flow studies, representing several steady-state conditions, must be considered in order to capture all relevant generation patterns induced by the presence of VRE sources.

Some differences exist in regard to the steady-state behaviour of low-voltage distribution networks and medium- and high-voltage networks. The specificities of low-voltage networks are described in Box 5.

Study results and evaluation criteria

The outcomes of load flow studies make it possible to assess the capability of the network to supply a given load with a given generation dispatch scenario. The criteria applied to analyse the results of the associated simulations are: voltage magnitude limits on each busbar of the system, branch (line, cable, transformer, etc.) thermal loading limits and network connectivity.

26 Load flow is also called “power flow”.

BOX 5: LOAD FLOW ANALYSIS OF LOW-VOLTAGE DISTRIBUTION NETWORKS

Low-voltage distribution systems differ from other types of power systems due mainly to the following characteristics:

- *Voltage level:* the distribution system is the final step of the delivery to end-consumers and is operated at a lower voltage level than transmission systems.
- *Network topology:* distribution systems typically have a radial or weakly meshed network.
- *Branch type:* distribution systems are composed of low-voltage, short-length overhead lines and cables, which are characterised by a high resistance/reactance ratio. The presence of single- and two-phase feeders is also common.
- *Load distribution:* load is usually distributed along the feeders, and phase unbalance is not uncommon.

Given the aforementioned characteristics, it is very important to use dedicated tools for performing load flow analysis in distribution networks given that conventional load flow tools are not capable of dealing with all of these particularities of distribution systems.

Regarding the input data required to perform load flow studies in low-voltage distribution networks, the following is required in addition to the data used for the analysis of transmission systems: distribution of the load along the feeder, load per phase, injection of distributed generation sources per phase and on-load tap changer transformer settings. The following outcomes are expected from a load flow study of low-voltage distribution systems: voltage magnitude per phase, power flows (active and reactive) and currents through each feeder and transformer, power injections per phase at each node, network losses and phase unbalance.

Special attention must be given to the impact of VRE penetration in the form of distributed generation, which can be summarised as follows:

- Presence of bi-directional power flows
- Over-voltage and voltage fluctuation problems due to the coupling between active power and voltage in low-voltage networks
- Change in power loss patterns
- Change in short-circuit levels.

The main findings of these studies are:

- violation of voltage magnitude ranges[27]
- equipment overloads[28].

The voltage magnitude ranges and branch overload criteria are (or should be) defined in specific regulatory documents (*e.g.,* the grid code) or power system planning guidelines.

Methodology to perform the study

Load flow studies generally are carried out through the use of computer simulation software packages. Numerous load flow software tools are available covering all basic features needed to perform load flow and static security assessment studies.

Power flows in a network are determined by the voltage at each busbar, the impedances of the network elements[29], the topology of the network, and the given generation dispatch and expected load at each busbar.

The load flow computation requires as input the network topology (status of circuit breakers and switches), the parameters of network elements (resistance, reactance, susceptance, capacity, etc.), the load[30] (active and reactive power) at each node, the active power dispatch of the generating units and the scheduled voltage at the terminal of the generating units.

27 Typical criteria (N condition): ± 5% of the nominal voltage. Note that the allowable voltage range increases under contingency and that allowable voltage ranges differs for different voltage levels.

28 Typical criteria (N condition): Lines, cables and transformers: nominal capacity of the equipment. Note that during contingency, some overload is allowed. The allowed overload is dependent on the element (transformer, line). Allowable overloads are further differentiated for different seasons of the year.

29 Network elements include lines, transformers, cables and compensation devices.

30 Customers are represented as aggregated loads with specified active (P) and reactive (Q) power. Depending on the study a load can represent a single customer or a whole distribution area (in larger systems).

The load flow software tools determine the set of voltages (magnitudes and phase angle) at each busbar that, together with the network impedances, generation dispatch and expected load, allows the calculation of the power flows through each branch of the network.

In the formulation of the load flow problem, each busbar is characterised by four dependent variables: injected power (active and reactive) and complex voltage (magnitude and phase). Two of these variables are known (green), while the other two are unknown (red), as depicted in Figure 20. The unknown variables are obtained as the solution of the load flow simulation.

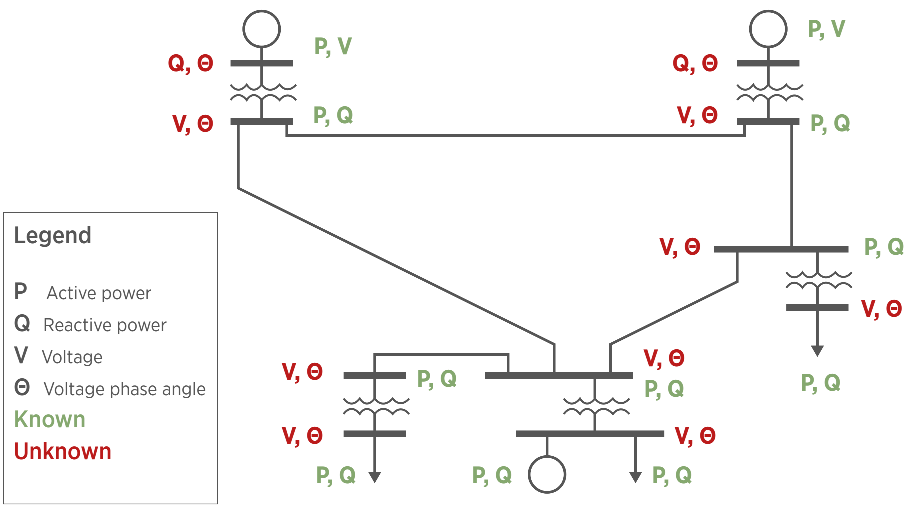
The load flow problem implemented in the many available software tools is formulated as a set of non-linear algebraic equations that relates the power injections at each node (load and generation) and the scheduled terminal voltage of the generating units to the impedance of the network. This set of equations enforces Kirchhoff's Law of Voltages and Kirchhoff's Law of Currents.

To assess the impacts of VRE penetration, the most critical scenarios from the point of view of system integration of VRE must be analysed, such as peak load, off-peak load, maximum VRE generation, etc. These scenarios are specified in the topic and the selection of scenarios for network studies in Section 3.3.

Analysis of results and next steps

Depending on the objective of the study, different measures are applied to solve possible problems detected through these studies. For example, if the objective of the study is to analyse the future expansion of the system (expansion planning), problems might be solved by specifying new investments in network reinforcement (new lines, cables, transformers, reactor/capacitor banks, etc.). However, if the study is intended for short-term operation (operational planning), investments in network reinforcement are not possible. In this case, operational measures such as, but not limited to, generation re-dispatch and network topology switching must be envisaged.

Figure 20: Principles of load flow computation



Adapted from: (Anderson and Fouad, 2003)

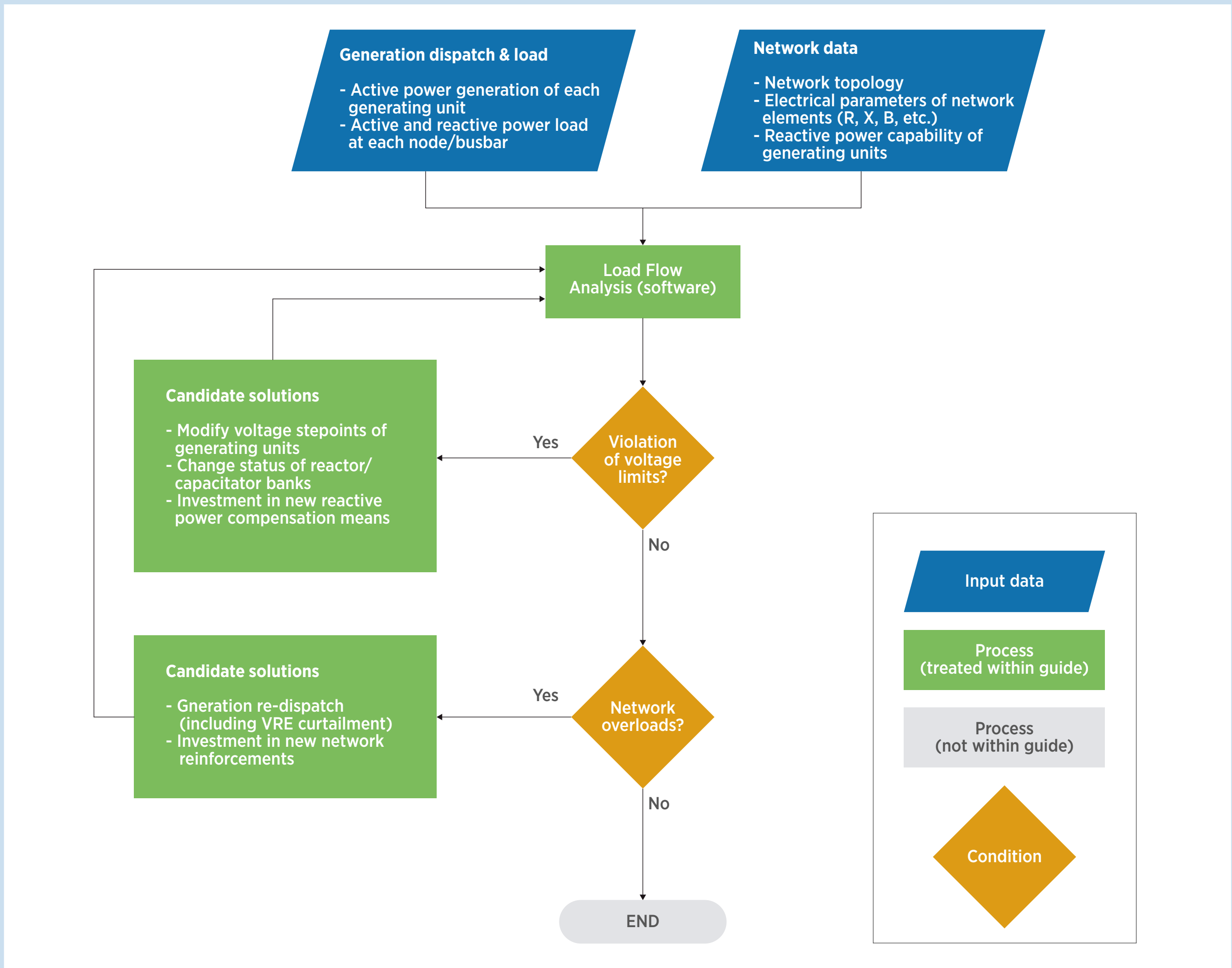
The results of load flow studies may indicate constraints to the maximum penetration level of VRE in the network. If that is the case, it is recommended to analyse appropriate solutions for increasing the VRE penetration and then to consider these solutions in a review of the study. More details on the relation between the study results and the solutions to be applied are given in Chapter 9.

Table 11 shows the conclusion that can be derived if violation of voltage magnitude ranges or equipment overloading are detected in load flow studies, and the potential solutions that can be adopted in expansion planning and operational planning. Table 12 summarises the main information required to perform a load flow study.

Table 11: Potential issues and solutions at the different planning stages for load flow studies

	Expansion planning	**Operational planning**
Violation of voltage magnitude ranges	• Insufficient amount of reactive power capacity is available: install new reactive power compensation equipment.	• The voltage set-points of the generating units are inadequate and must be adapted. • Insufficient amount of reactive power capacity is available: switch on/off existing reactive power compensation equipment. • VRE generation curtailment might be needed to restore voltage to acceptable limits (typically in low-voltage networks, where voltage and active power are intrinsically coupled).
Equipment overloads	• Investments in network reinforcement (new lines, cables, transformers, reactive power compensation devices, etc.) are needed.	If significant amount of reactive power transfer is detected, a review of reactive power compensation, transformer's tap position and/or voltage set-points of the generating units is needed. • Generation re-dispatch needs to be carried out to alleviate network overload in case of very high active power transfer. Note that re-dispatching is sensitive to the size of the power system. For instance, small systems have limited, if any, possibility to re-dispatch due to other operational constraint (*e. g.*, need of voltage support); • VRE generation curtailment might be needed to restore power flows to acceptable limits.

Figure 21: Workflow to perform load flow studies



Workflow to perform the study

Figure 21 synthesises in a workflow how to perform load flow studies.

Examples of study results

This section synthesises the conclusions obtained by means of load flow studies under a solar power integration study on the Seychelles Islands (Brown *et al.*, 2016). The electrical network of Mahé island, composed of 11 kV and 33 kV circuits, is presented in Figure 22.

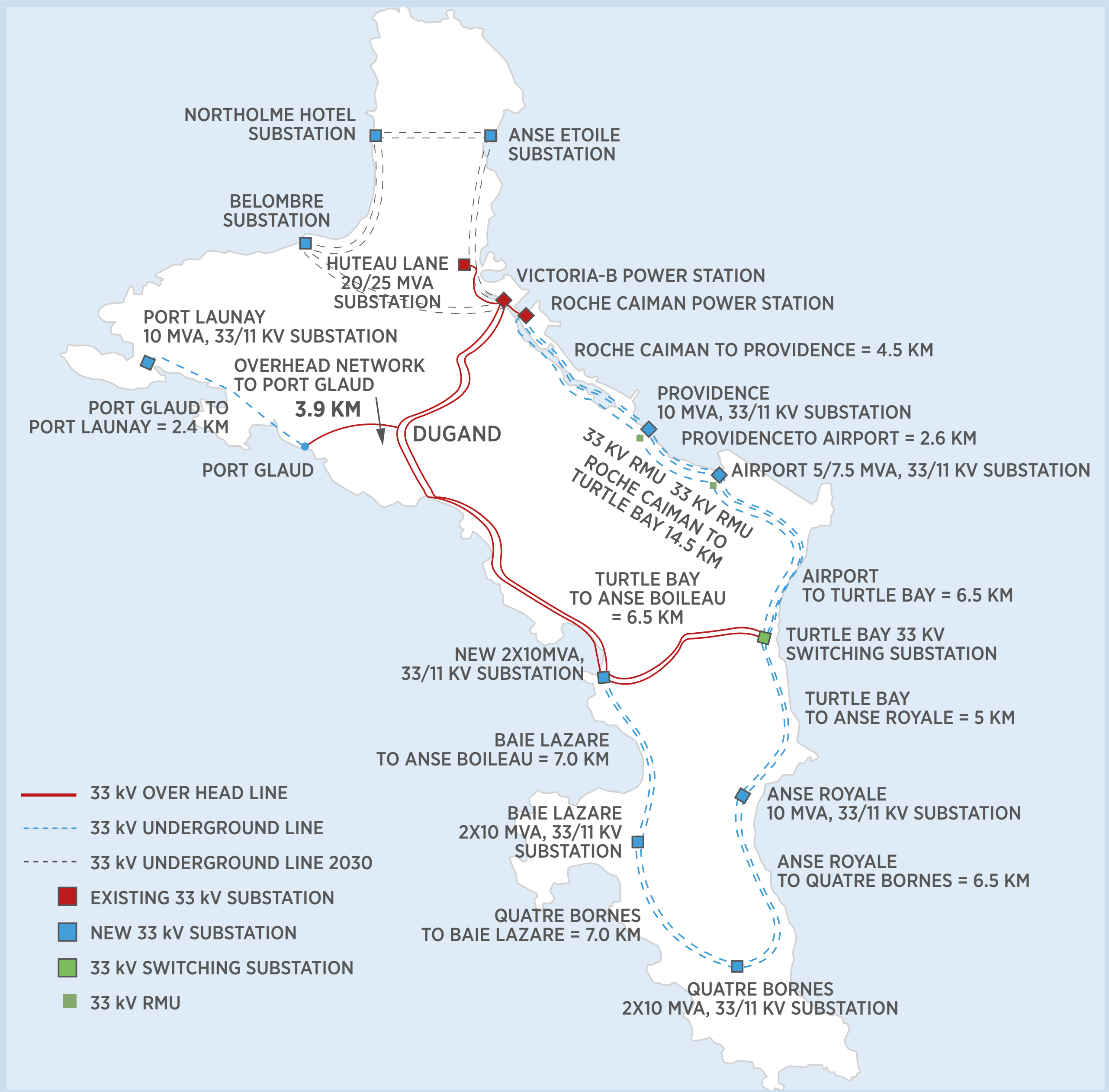
The load flow studies for different target years aim to identify the limits of solar PV integration for this system. The main conclusions derived from this study are the following:

- For the system condition in the year of study, under-voltage and network overload problems were identified in the south of Mahé due to the rising load.
- By 2030, under-voltage and overload problems would occur in North Mahé due to the rising load in this region. Network reinforcements were proposed to mitigate these problems.
- Regarding the limitations for solar PV integration, no specific constraints were identified in the load flow study.

References for further reading

- Theory of Power System Analysis: Grainger and Stevenson, Jr. (1994)

Figure 22: Electrical network of Mahé island



Source: Brown *et al.*, 2016. Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

Table 12: Summary of load flow studies

Requirement	Description
Model requirements	• Network: positive sequenceT/three-phaseD alternating current load flow model with existing or planned topology, as well as typical operation scheme (breaker status, etc.). • VRE sources: aggregated P/Q (active/reactive power) injections or P/V (active power/ voltage set-point) at the point of connection. • Other generation: P/Q injection or P/V at the output of each unit. • Load: P/Q consumption at each busbar where a load is connected.
Input data	• Generation dispatch, load at each node, network topology, parameters of lines and cables (length, resistance, reactance, susceptance, etc.), parameters of transformers (nominal voltage, short-circuit impedance, etc.), parameters of generators (type, connection point, rated power, min/max active/reactive power, etc.), shunt compensation parameters (type, connection point, rated power, etc.), parameters of high-voltage direct current /flexible alternating current transmission systems (FACTS), etc. Ideally this information is made available under a single-line diagram and/or a geographic information system (GIS) model with the length of the lines/cables.
Methodology	• Build the network static model (topology and characteristic of the equipment). • Set expected demand and generation dispatch according to the scenario to analyse. • Launch positive sequenceT/three-phaseD load flow computation. • Analyse results.
Scenarios	See Section 3.3: selection of scenarios for network studies.
Criteria for the analysis of results	• Voltage magnitude range in normal operating conditions[T&D]. • Line/cable thermal limits in normal operating conditions[T&D]. • Transformer thermal limits in normal operating conditions[T&D]. • Violation of power capability curve of the generating units[T&D]. • Phase voltage and current unbalance (three-phase load flow)[D].
Outcomes of the simulation	• Voltage magnitude and phase at each node[T&D]. • Power flows (active and reactive) through each element of the network[T&D]. • Power injections at each node[T&D]. • Network losses[T&D]. • Phase unbalance[D].
Interpretation of the simulation results	If simulation results indicate violation of voltage limits and/or branch thermal capacity, the possible operational solutions to be analysed are: generation re-dispatch, network topology modifications, and modification in reactive power compensation means. In the case of network expansion planning, network reinforcement aimed at solving the detected problems should be analysed. Load flow results are also used to define the reactive power capability requirements for generating units (including VRE) that should be included in the grid code. Finally, setting a VRE penetration limit for the given operating condition could be needed.
Examples of available software tools	• Transmission and distribution: PowerFactory (DIgSILENT GmbH), ETAP (ETAP), NEPLAN (NEPLAN AG), PSS/E (Siemens PTI). • Transmission: PowerWorld Simulator (PowerWorld Corporation), PSLF (GE), SmartFlow (Tractebel). • Distribution: CymDist (CYME International Inc.), DEW/ISM (EDD), GridLab-D (U.S. DOE), OpenDSS (EPRI), Smart Operation (Tractebel), Synergi Electric (DNV-GL).

[T]: Transmission; [D]: Distribution

6.2. Static security assessment

Power system security can be defined as the ability of a power system in normal operation to undergo a likely disturbance without entering an emergency or a restorative state (see below).

Static security analysis evaluates the security of the system after the occurrence of one (N-1) or more (N-k) contingencies, once steady-state conditions are reached (*i. e.,* neglecting transient behaviour and any other time-dependent variations due to changes in load, generation and network conditions).

The typical contingency employed in this kind of study is to consider the outage of a single system element at a time, the so-called N-1 criterion. This is an important and globally recognised planning criterion to ensure that the system must remain stable, must not present overloading of lines and transformers over a certain level and must keep all voltages in a given range even in any N-1 situation.

However, existing small-island power systems are usually weak and do not fully comply with the N-1 criterion for the entire system (*i. e.,* radial parts of the network). In this case, within the framework of expansion planning and operational planning, it is important to identify the most probable contingencies, also known as normative incidents (based on a statistical analysis of past incidents[31] in the network or the experience of the operator of the grid), and then perform the study based on this sub-set of possible contingencies.

Security assessment is the analysis performed to determine whether, and to what extent, a power system is reasonably safe from serious interference to its operation. In other words, it is the process of determining if the power system is in a secure state or an alert state. The definition of power system states is given as follows:

- ***Normal (secure):*** the system is within operational security limits in the intact situation and after the occurrence of any normative incident.

- ***Alert:*** the system is within operational security limits, but a normative incident has been detected for which, in case of occurrence, the available remedial actions are not sufficient to maintain the normal state.

- ***Emergency:*** the operational security limits are violated and at least one of the operational parameters is outside of the respective limits.

- ***Blackout:*** the operation of part or all of the power system is terminated.

- ***Restoration:*** state in which the objective of all activities is to re-establish system operation and to maintain operational security after blackout or emergency state.

This kind of study is not applicable to low-voltage distribution networks due to the radial structure of these systems.

Study results and evaluation criteria

The outcomes of static security assessment study make it possible to assess the capability of the network to supply a given load with a given generation dispatch scenario under contingency. The criteria applied to analyse the results of the associated simulations are: voltage magnitude limits on each busbar of the system, branch (line, cable, transformer, etc.) thermal loading limits and network connectivity. These limits are usually different (higher, but for a limited period of time) from the ones used for load flow studies.

The main findings of this study are:

- Violation of voltage magnitude ranges[32]
- Equipment overloads[33].

31 Also known as "secured contingencies".

32 Typical criteria (N-1 condition): ± 10 % of the nominal voltage

33 Typical criteria (N-1 condition): lines and cables 110 %; transformers 120 %

The voltage magnitude ranges and branch overload criteria are (or should be) defined in specific regulatory documents (usually in the grid code). These criteria are defined while considering that the contingency will occur only for a limited amount of time so that the potential overload or under/overvoltage will not permanently affect the equipment.

Methodology to perform the study

A full load flow model, followed by a convergent load flow solution that complies with all planning criteria, is needed to perform a static security assessment study.

To assess the impacts of VRE penetration, the most critical scenarios from the point of view of system integration of VRE must be analysed. These scenarios are specified in the topic selection of scenarios for network studies in Section 3.3.

In addition, a set of contingencies for which the power system should be able to remain in operation for a limited amount of time must be defined (list of normative incidents). Static security assessment is generally carried out through the use of specific computer software packages. Usually, the software tool that enables performing load flow computations has a built-in module for static security assessment (contingency analysis module). For each normative incident, the software automatically disconnects the involved equipment and then performs a new load flow simulation.

Analysis of results and next steps

Depending on the objective of the study, different mitigation measures are applied to solve possible problems detected through these studies. In particular, the results of static security assessment may indicate constraints to the maximum penetration level of VRE in the network. If that is the case, it is recommended to analyse appropriate solutions for increasing the VRE penetration and then to consider these solutions in a review of the study.

For example, if the objective of the study is to analyse the future expansion of the system (expansion planning), problems might be solved by specifying new investments in network reinforcement (new lines, cables, transformers, reactor/capacitor banks, etc.). However, if the study is intended for short-term operation (operational planning), investments in network reinforcement are not possible. In this case, operational measures such as generation re-dispatch and network topology switching must be considered.

Table 13 provides preventive and corrective measures that can be adopted in the event that violation of voltage magnitude ranges and equipment overloads are detected.

Note that at the expansion planning stage, the objective is to minimise the number of corrective measures needed to comply with the planning criteria under a contingency

Table 13: Potential measures at the different planning stages for static security assessments

	Expansion planning	Operational planning
Preventive measures	Investment in network reinforcement to ensure that the system remains secure after the occurrence of normative contingencies.	Active and/or reactive power re-dispatch to avoid a situation where an incident that should be secured (normative incident) results in voltage collapse or network overloads.
Corrective measures	Implementation of special protection schemes (SpPS) triggered after an incident, such as automatic generation re-dispatch or intelligent load shedding.	Implementation of SpPS triggered after an incident, such as automatic generation re-dispatch or intelligent load shedding. Automated load management system able to minimise the amount of load shedding.

situation. In this planning horizon, corrective measures are justified only when the preventive measures are much too expensive. Preventive measures are those that ensure a secure operating condition after a normative contingency without needing any action from the system operator immediately after contingency.

Corrective measures are triggered after the incident in order to drive the post-incident system to an acceptable operating condition.

Preventive measures usually result in higher security margins but at higher operating costs.

Workflow to perform the study

This kind of study is not applicable to low-voltage distribution networks due to the radial structure of these systems. Figure 23 synthesises in a workflow how to perform static security assessment studies. Table 14 provides a summary of the methodology for performing static security assessment of the system.

Figure 23: Workflow to perform static security assessment studies

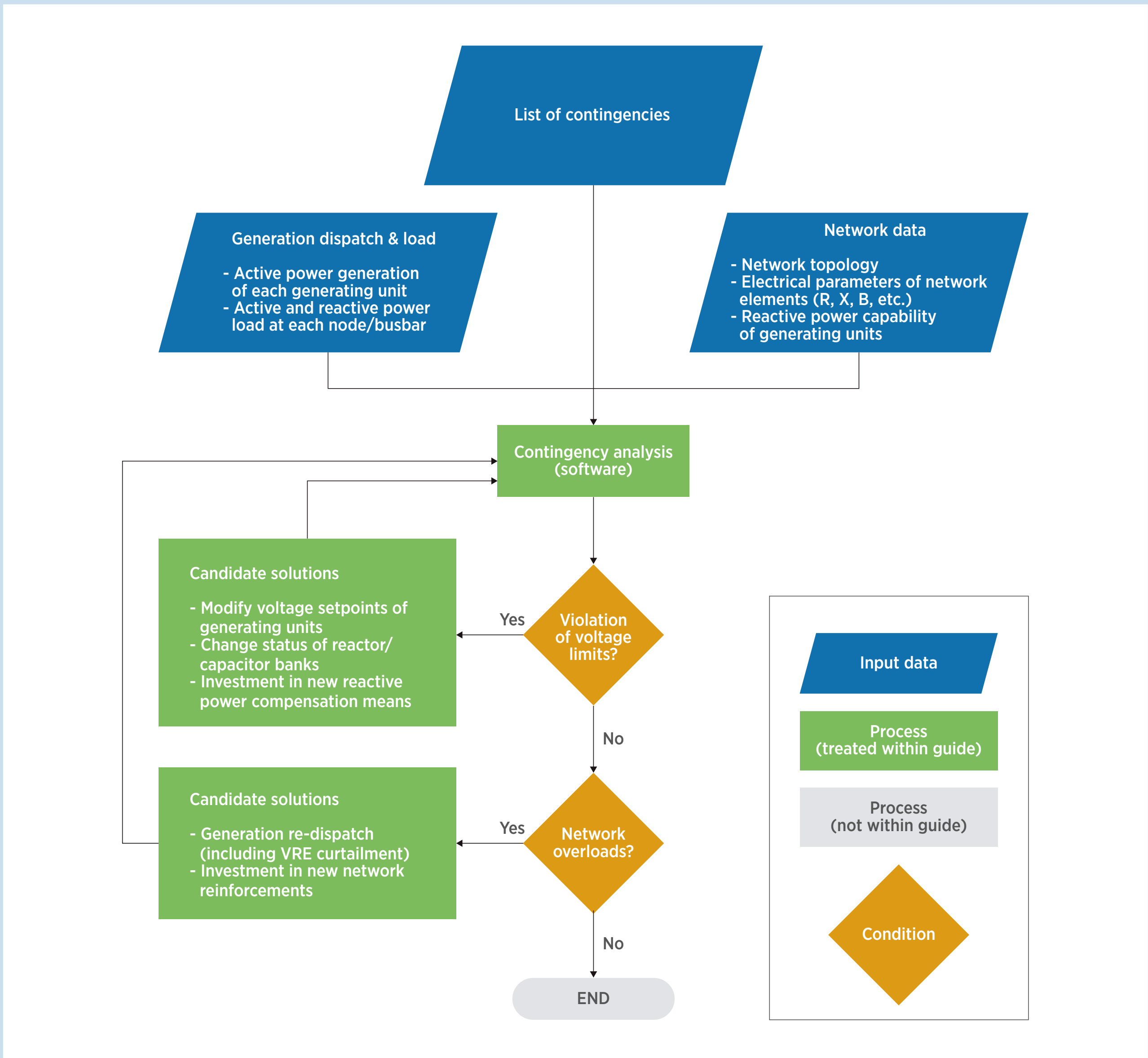


Table 14: Summary of static security assessment

Requirement	Description
Model requirements	• Convergent alternating current load flow. • List of contingencies (must include all normative contingencies). • Operational/planning criteria (voltage ranges and equipment overload capacity).
Input data	Same as presented in Table 12.
Methodology	• Set the operational/planning criteria. • Set the list of normative contingencies. • Launch static security assessment computation. • Analyse results.
Scenarios	See Section 3.3: selection of scenarios for network studies.
Criteria for the analysis of results	• Voltage magnitude range under contingency conditions. • Line/cable thermal limits under contingency conditions. • Transformer thermal limits under contingency conditions. • Violation of power capability curve of the generating units.
Outcomes of the simulation	• Voltage magnitude and phase at each node. • Power flows (active and reactive) through each element of the network. • Power injections at each node.
Interpretation of the simulation results	If simulation results indicate violation of voltage limits and/or branch thermal capacity, a VRE penetration limit for the given operating condition might have to be set. In the case of network expansion planning, network reinforcement aimed at solving the detected problems should be analysed. Operational planning solutions to be analysed are: generation re-dispatch, network topology modifications, modification on reactive power compensation means. Load flow results are also used to define the reactive power capability requirements for generating units (including VRE) that should be included in the grid code.
Examples of commercial software tools	• PowerFactory (DIgSILENT GmbH), ETAP (ETAP), NEPLAN (NEPLAN AG), PowerWorld Simulator (PowerWorld Corporation), PSLF (GE), PSS/E (Siemens PTI), SmartFlow (Tractebel).

6.3. Short-circuit currents

A short circuit is one of the major incidents affecting electrical systems. A short circuit can be defined as an abnormal connection between two or more conductors (and/or to ground) of different phases in a line, transformer or any other element of a power system through which the current tends to flow rather than along the intended path.

The importance of performing short-circuit current studies can be highlighted considering the following consequences of a short circuit (Merlin Gerin, 2006):

- A short circuit disturbs the power system around the fault point by causing a sudden drop in voltage.

- It requires disconnection, through the operation of protection devices, of a part of the network.

- All equipment and connections (cables, lines) subjected to a short circuit are subjected to high mechanical stress (electrodynamic forces) that can cause breaks and thermal stress that can melt conductors and destroy insulation.

- At the fault point, there is often a high-energy electrical arc, causing very heavy damage that can quickly spread.

The design and sizing of an electrical installation and the associated equipment, as well as the determination of the required equipment and human life protection, require the calculation of short-circuit currents for every point in the network.

The short-circuit current at different points in the power system must be calculated to design the cables, busbars, and all switching and protection devices and determine their settings.

From the point of view of VRE integration, short-circuit current studies aim to ensure no violation of equipment short-circuit current rating, as well as to guarantee a minimum short-circuit power at the point of connection of the VRE generators.

Note that the contribution of VRE power plants to the short-circuit current may differ from those of classic power plants equipped with synchronous machines. VRE sources are usually interfaced with the network via power electronics devices, which are known for their limited short-circuit currents (usually about 1.1 times the nominal current).

The integration of VRE sources might lead to a decrease in short-circuit current levels, which is beneficial in terms of avoiding violation of equipment short-circuit current limits, but it also may result in additional challenges to protection system co-ordination and selectivity due to very low short-circuit current levels.

There are two main aspects for analysing short-circuit current studies in the expansion planning and operational planning phases:

- Ensure that the short-circuit currents will not exceed the rated capacity of the network equipment (circuit breakers, busbars, etc.).

- Ensure that a minimum short-circuit current level is achieved in order to guarantee proper protection co-ordination and selectivity.

Study results and evaluation criteria

The main findings of short-circuit current studies are:

- violation of interruption capacity of circuit breakers (circuit breakers must be able to interrupt every fault current);

- violation of busbar thermal capacity (see previous paragraph);

- minimum short-circuit levels or short-circuit ratio to ensure protection co-ordination and selectivity.

Methodology to perform the study

For static analyses, assessing the impacts of VRE penetration requires analysing the most critical scenarios from the point of view of system integration of VRE. These scenarios are specified in the topic selection of scenarios for network studies in Section 3.3.

Normally, short-circuit studies involve the computation of three-phase to ground fault condition. This usually establishes a "worst case" (highest current) condition that results in maximum three-phase thermal and mechanical stress in the system (Cooper Bussmann, 2005).

In addition to the input data, the method used to perform the calculation of short-circuit currents must be defined before performing the study. Several methods (impedance method, symmetrical components method, etc.) and standards (IEC 60909 and 61363, ANSI/IEEE C37 and UL 489, etc.) are available for computing short-circuit currents. These methods and standards often simplify the calculation to different degrees, which otherwise would require a very detailed simulation of the system.

Usually, power system analysis software tools provide the most widely used options and methods to compute short-circuit currents. The method used to perform these computations is usually specified in the grid code or in the power system planning guidelines of the country.

Short-circuit current studies are generally carried out through the use of computer software packages. A variety of short-circuit current software tools are available that cover all of the minimum aspects needed to perform basic short-circuit computations. The user is often given the possibility to select different methods/standards to perform the computation.

To determine the fault current at any point in the system, all input data needed for performing load flow computation is needed. Additionally, short-circuit impedance of generating units, type of loads, rated capacity of circuit breakers and busbars and sequence parameters of the equipment (positive, negative and zero)[34] are required.

Inverter-based VRE is usually modelled as a synchronous machine with a given short-circuit impedance level that results in short-circuit current levels indicated in the inverter's datasheet.

Analysis of results and next steps

Depending on the objective of the study, different measures are applied to solve possible problems detected through short-circuit current studies. For static studies, if the objective is to analyse the future expansion of the system (expansion planning), problems of short circuit might be solved by specifying new investments in network reinforcement (upgrading to a higher voltage level, splitting/meshing the network, etc.). However, if the study is intended for short-term operation (operational planning), operational measures such as network topology switching must be envisaged.

Workflow to perform the study

Figure 24 synthesises in a workflow how to perform short-circuit studies. Table 15 provides a summary of the methodology for performing short-circuit current analyses.

References for further reading

- Short-circuit current theory and calculation methods: Schneider Electric (2005)
- Power System Analysis and Design, Ch. 7, 8 and 9: Glover et al. (2011).

34 Sequence parameters are only needed if computation of asymmetrical faults is necessary. For more details see "References for further reading".

Figure 24: Workflow to perform short-circuit studies

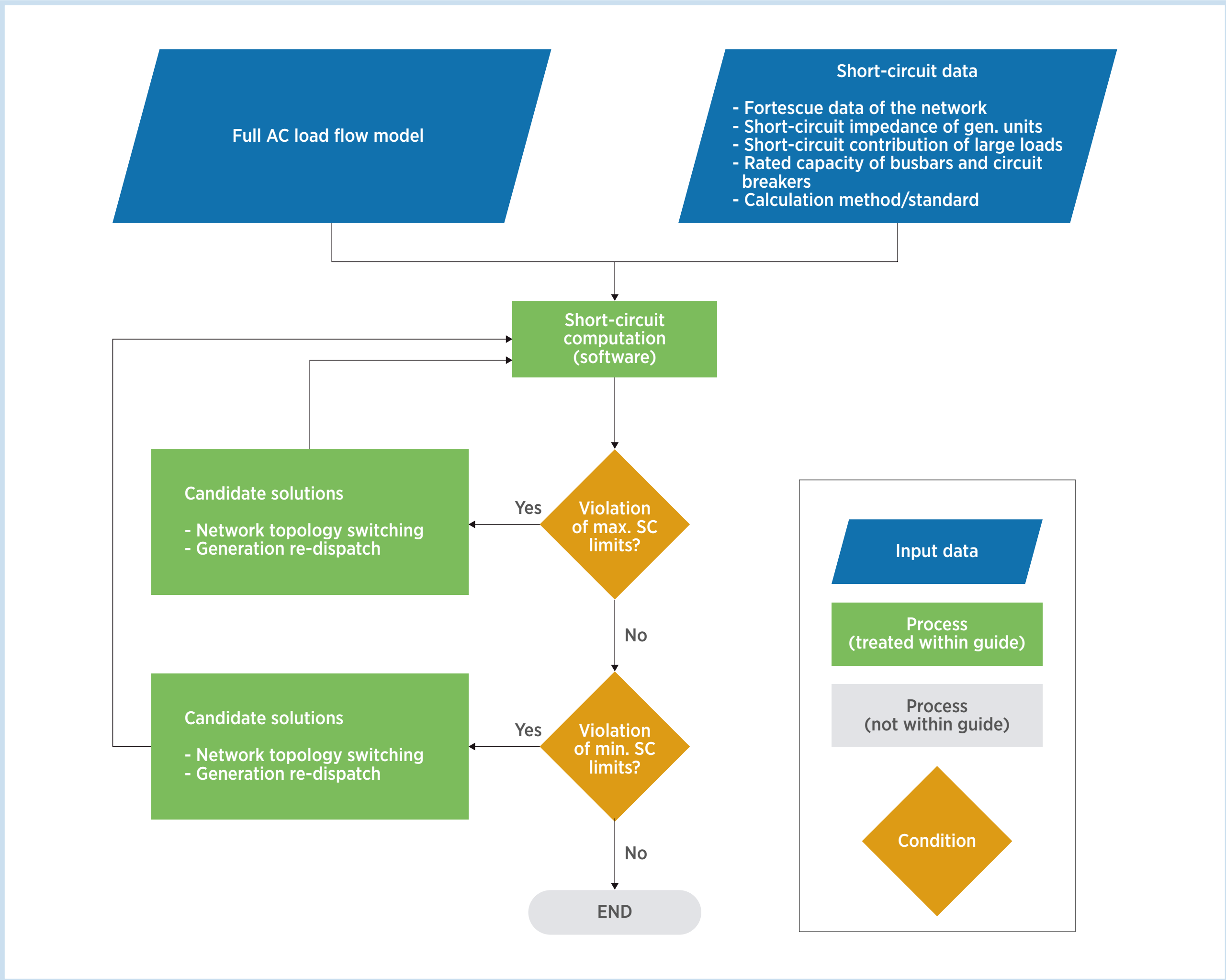


Table 15: Summary of short-circuit current analysis

Requirement	Description
Model requirements	Same as presented in Table 12, as well as: • Applicable standard for short-circuit computation (*i. e.*, IEC 60909).
Input data	Same as presented in Table 12, as well as: • Short-circuit impedance of generating units • Short-circuit contribution of the loads • Rated capacity of circuit breakers and busbars • Sequence parameters of the equipment (positive, negative and zero).
Methodology	• Check the static model used for load flow analysis. • Launch short-circuit current calculation. • Analyse results.
Scenarios	See Section 3.3: selection of scenarios for network studies.
Criteria for the analysis of results	• Violation of interruption capacity of circuit breakers. • Violation of busbar thermal capacity. • Minimum short-circuit levels to ensure protection co-ordination and selectivity.
Outcomes of the simulation	• Short-circuit currents at each busbar and circuit breaker. • Assessment of minimum short-circuit levels to ensure protection co-ordination and selectivity.
Interpretation of the simulation results	If the objective of the study is to analyse the future expansion of the system (expansion planning), problems might be solved by specifying new investments in network reinforcement (upgrading to a higher voltage level, splitting/meshing the network, upgrade circuit breakers, etc.). However, if the study is intended for short-term operation (operational planning), operational measures such as network topology switching must be envisaged.
Examples of commercial software tools	• PowerFactory (DIgSILENT GmbH), ETAP (ETAP), NEPLAN (NEPLAN AG), PSLF (GE), PSS/E (Siemens PTI), SmartFlow (Tractebel).

7. NETWORK STUDIES FOR SYSTEM PLANNING IN SMALL ISLAND DEVELOPING STATES: SYSTEM STABILITY STUDIES

This chapter presents an overview of system stability studies in view of accommodating increasing levels of VRE in the power systems of SIDS. The three different types of simulations performed for this category of studies are:

- transient stability
- frequency stability
- voltage stability.

System stability is one of the main challenges for the operation of small-island power systems. Stability can be defined as the ability of a system to regain a steady-state operating condition following a disturbance. Therefore, system stability represents the robustness of the system against both small disturbances that occur continuously (*e. g.,* load fluctuations) and severe disturbances (*e. g.,* loss of a large generator, etc.).

Power system stability can be classified considering the following aspects (Kundur et al., 2004):

- the physical nature of the resulting mode of instability (indicated by the main system variable in which instability can be observed);

- the amplitude of the disturbance considered;

- the devices, processes and time span that must be taken into account to assess stability.

Based on the aforementioned aspects, the following power system stability phenomena can be defined (M.P.E. GmbH, 2013):

- ***Frequency stability:*** ability of a power system to balance active power (generation and load) and to maintain frequency within a narrow range around the nominal frequency.

- ***Voltage stability:*** ability of a power system to maintain a steady-state voltage at all busbars following a disturbance.

- ***Rotor angle stability:*** ability of the synchronous machines in a power system to remain in synchronism following a disturbance.

System stability assessment of small-island power systems differs from stability analysis of large interconnected power systems due to the following aspects (IRENA, 2015a):

- reduced number of conventional generating units (consequence: low system inertia, loss of a generator can be critical);

- tendency of high shares of VRE generation with corresponding high power output fluctuations;

- small and weakly meshed network structure;

- different load-frequency control strategies;

- limited means to face instabilities other than load shedding.

In addition, the absence of a grid code for small-island power systems complicates stability assessments since no specified technical requirements are imposed to generators and loads, defined on the basis of power system analysis. In that case, a dedicated study should be carried out or standard requirements could be adopted.

System stability studies are carried out through power system dynamics simulations. The following preconditions must be fulfilled to be able to perform a power system stability study (IRENA, 2015a):

- load flow study
- short-circuit currents study
- generation dispatch study.

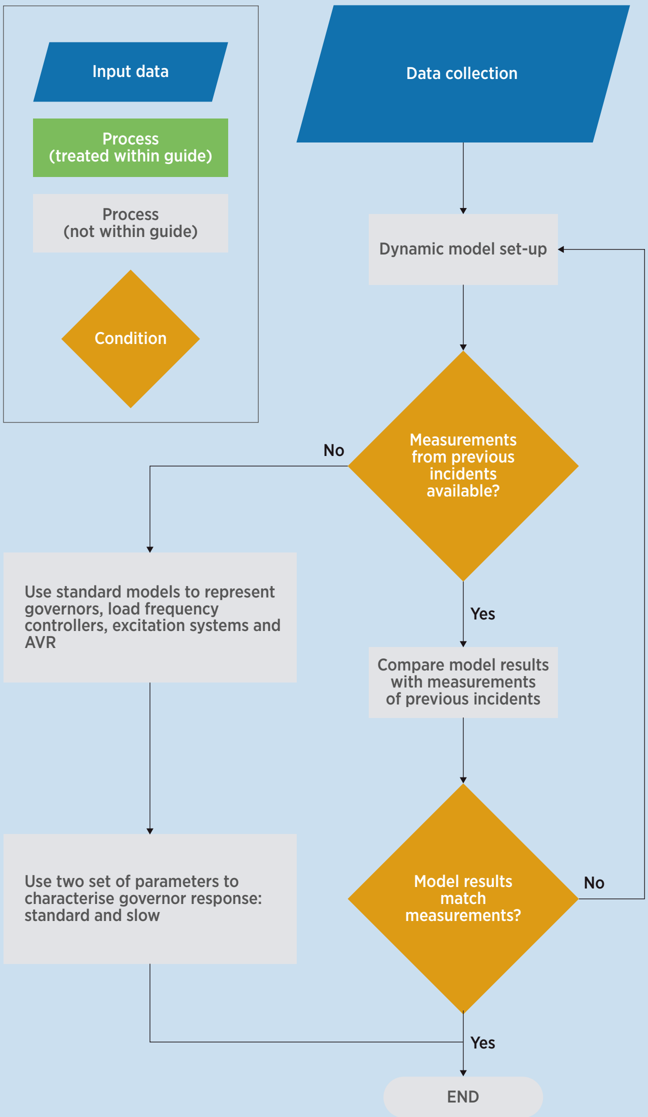
More details on power system stability theory, as well as a complete description of the methodology for developing a dynamic model of a power system, can be found in IRENA (2015a) and in Sigrist et al. (2016).

The first step for performing system stability studies is development of the dynamic model of the power system. Box 6 presents a general overview of this process. More details on the dynamic modelling exercise can be found in IRENA (2015a) and in Sigrist *et al.* (2016).

The guidelines for performing transient, frequency and voltage stability studies are presented in the following sections.

BOX 6: DEVELOPMENT OF A POWER SYSTEM DYNAMIC MODEL

The flow chart presented below depicts the process of developing and validating a dynamic model of a power system. More details regarding this process are provided in IRENA (2015a).



7.1. Transient stability

Transient stability refers to the ability of the power system to maintain synchronism following a transient disturbance[35] (Kundur, 1994). Synchronism can be defined as the ability of synchronous machines to operate in parallel at the same angle difference (with reference to a fixed angular reference) and at the same rotor speed (measured in electrical radians per second).

The phenomena that are typically observed in a transient stability study are presented as follows:

- Faults will lead to transient voltage depletion and to restrictions in power transfer. Usually, synchronous generators will accelerate during the fault and rotor angle will increase.
- Synchronous generating units closest to the fault will experience the greatest electrical power decrease and will accelerate faster than units electrically far from the fault.
- For the same amount of lost load during the fault, synchronous generators with lower inertia will accelerate more quickly. Generators within the same power plant may remain in step with each other while diverging from the apparently higher inertia grid infeed.
- Induction motor (load) slip will increase during the fault (chance of motor stalling).

The system is stable if, after fault clearance (by tripping the faulted element or due to the temporary nature of the fault):

- the rotor angle swings are damped;
- voltages and frequency return to a post-fault steady-state operating condition;
- induction motor slips return to normal load values.

Transient stability margin can be measured in terms of the critical clearing time (CCT), which is defined as the maximum fault duration for which all synchronous generators in a power system remain in synchronism after the protection system clears the fault[36] by tripping the faulted element. For secure and reliable power system operation, the CCT is required to be higher than the actual fault clearing times of the network protections. If this can be verified, transient stability problems are not likely to happen as long as the protection devices operate accordingly.

VRE sources interfaced with the grid via power electronics-based devices are not directly affected by transient stability issues. However, these sources can have an indirect impact on CCTs. This impact can result from one or a combination of the following aspects (M.P.E. GmbH, 2013):

- modified system inertia (*i. e.,* fewer rotating masses);
- increased power transfers through the network (*i. e.,* VRE sources far from the load);
- reduced voltage support during voltage recovery (*i. e.,* remote location and limited reactive power capability of VRE sources);
- reduced synchronising torques between remaining synchronous generators (*i. e.,* easier loss of synchronism).

The impact of VRE sources on CCT can be positive or negative. Therefore, it is not possible to make a general statement on the impact of VRE sources in power system transient stability without performing a transient stability study.

35 A transient disturbance is an abrupt variation of voltage and current for a short duration of time, usually as a result of a short circuit.

36 Permanent or temporary short circuits.

Study results and evaluation criteria

A transient stability study usually has three main objectives:

- assess if the system remains stable after a fault is cleared in base time by tripping the faulted element[37] (also known as dynamic security assessment or DSA);
- determine the transient stability margin of the system for a given fault and system operating condition;
- assess the fault ride through (FRT) – both low-voltage ride through and high-voltage ride through – capability of the generating units.

Dynamic security assessment (DSA)

In a DSA study, ***faults cleared in base time***[38] are simulated in order to verify if the system is stable from the viewpoint of transient stability following normal operation of the network protection schemes.

The evaluation criteria used to determine if the system is stable or not after fault clearance are the following:

- no generating unit is tripped due to the action of its protections (over-/under-speed relays, over-/under-voltage relays, LVRT/HVRT disconnection protection, etc.);
- voltage recovery criteria, *e.g.*:
  - V > 0.70 pu within 500 ms after fault clearance
  - V > 0.90 pu within 10 seconds after fault clearance;
- no machine loses synchronism.

If a fault leads to an unstable operating condition, preventive or corrective measures should be foreseen in order to ensure secure and stable system operation.

Critical clearing time (CCT) computation

Another objective of transient stability analysis is to determine the ***stability margin of the system***. This stability margin is measured in terms of the CCT. The CCT is defined as the maximal fault duration for which the system remains transiently stable.

In practice, CCT is computed through iterative analysis of system post-disturbance conditions (iterative dynamics simulations with increasing fault duration until the system becomes unstable) (Boussahoua and Boudour, 2009).

The evaluation criteria for CCT computations are the following:

- CCT must be strictly higher than the protection base time plus a margin defined by the planner;
- if CCT is lower than the protection stuck breaker or backup times, it is necessary to implement adequate protection schemes (*i. e.,* out-of-step relays) to adequately manage the consequence of the out-of-synchronism conditions.

Fault ride through (FRT) capability of generating units

The third aspect analysed in a transient stability study is the FRT capability of the generating units of the system. The FRT defines a set of thresholds (see Figure 27) within which each generating unit must remain connected to the system until the faulted element has been cleared from the network.

If a generating unit is not capable of "riding through" a fault in the system, it would be susceptible to tripping when subject to a voltage dip at its point of connection. If left unchecked, the consequences would be significant loss of generation and frequency collapse followed by a blackout.

37 Considering tripping the faulted element is only possible for cases where the N-1 criterion is met. When this is not the case, only temporary faults are simulated.

38 Typically five or six cycles (100 or 120 ms for a 50 hertz system).

The evaluation criteria used to determine if the system is stable or not after fault clearance is the following:

- no generating unit is tripped due to the action of its LVRT or HVRT protection.

Methodology to perform the study

Development of a dynamic model of the small-island power system is required to perform a transient stability study. The same model is used for DSA, FRT and CCT analyses. What differs from one analysis to the next is the type of incident to be simulated and the type of result analysis to be carried out. As mentioned before, a convergent load flow solution complying with all operational criteria must be available beforehand to allow for power system dynamics simulation.

Dynamic security assessment (DSA) and fault ride through (FRT) capability of generating units[39]

To perform DSA and FRT assessments, it is necessary to define a list of normative incidents. The following are usually employed in this kind of analysis:

- three-phase-to-ground short circuit cleared by tripping the faulted network element (line or transformer) in base time (five or six cycles): only applicable to N-1 compliant contingencies;

- transient three-phase-to-ground short circuit (five or six cycles): only applicable to N-1 non-compliant contingencies.

A time-domain power system dynamic simulation must be performed for each normative incident or at the most severe locations in the network. The recommended simulation duration is between 10 and 15 seconds, depending on the system and its dynamics. Once the simulations are finished, verification of the different criteria presented previously must be performed.

39 Note that DSA is usually performed only in meshed systems, given that in radial systems clearing the fault by tripping the faulted element leads to load or generation disconnection.

Critical clearing time (CCT) computation

To perform CCT computation, it is necessary to define a list of incidents for which the CCT must be determined. The following are usually employed in this kind of analysis:

- three-phase-to-ground short circuit cleared by tripping the faulted network element (line or transformer): only applicable to N-1 compliant contingencies;

- transient three-phase-to-ground short circuit: only applicable to N-1 non-compliant contingencies;

- single-phase-to-ground short circuit in case of radial connection with only one circuit.

Note that for CCT computation the fault duration is not input information, but rather a problem variable.

A time-domain power system dynamic simulation must be performed for each normative incident. The recommended simulation duration is between 10 and 15 seconds. It is recommended to start the CCT computation with a fault duration time of five or six cycles (usually 100 ms) and then to progressively increase (steps of one cycle are recommended) it until system instability is detected. The CCT value will be equal to the fault duration used in the latest stable simulation.

Once the simulations are finished, verification of the different criteria presented previously must be performed.

Analysis of results and next steps

Depending on the objective of the transient stability study, different measures can be applied to solve possible problems identified. For example, if the objective of the study is to analyse the future expansion of the system (expansion planning), problems might be solved by specifying new investments in network reinforcement (new lines, cables, transformers, reactor/capacitor banks, etc.). However, if the study is intended for short-term operation (operational planning), investments in network reinforcement are not possible. In this case, operational measures such as generation re-dispatch and network topology switching must be envisaged.

For more details on the relation between the study results and the solutions to be applied, see Chapter 9. Table 16 provides a list of potential issues and solutions at the different planning stages for transient stability studies.

Workflow to perform stability studies

Figure 25 synthesises in a workflow how to perform transient stability studies. This workflow is common to all stability studies including transient, frequency and voltage stability.

Examples of study results

The figures below present the results of a transient stability study that was carried out to determine the LVRT characteristic of a power system in order to update the grid code requirements for VRE integration. In this study, three-phase-to-ground short circuits cleared in backup time[40] were simulated at every node of the system. Then, the voltage response at each node (for each simulated incident) was plotted in a single figure so as to estimate the envelope (curve in red) of voltage response of the system (see Figure 26).

Table 16: Potential issues and solutions at the different planning stages for transient stability studies

	Expansion planning	**Operational planning**
Dynamic security assessment (DSA)	• If system is unstable for a given incident, network reinforcement might be needed.	• If system is unstable for a given incident, generation re-dispatch (both active and reactive power) or network topology switching might be needed. • In case system stability cannot be guaranteed for faults cleared in base time, special protection schemes (or accelerated network protection) must be put in place.
FRT capability of generating units	• Develop grid code requirements for LVRT/HVRT of generating units in case these requirements do not actually exist. • Enforce that every new generating unit comply with LVRT/HVRT characteristics imposed by the grid code.	• If it is detected that some generating units are disconnecting from the network during or just after faults, corrective actions from the operator must be put in place in order to avoid system blackout due to these disconnections. • Enforce that every new generating unit comply with LVRT/HVRT characteristics imposed by the grid code.
Critical clearing time (CCT) computation	• Network reinforcement could be foreseen in case the CCT is lower than the stuck breaker and/or backup protection times in order to improve system stability margins. • In case network reinforcement is not economically feasible, installation of out-of-step relays is required.	• Out-of-step relays must be installed and properly tuned in case the CCT is lower than the backup protection times. • If CCT is higher than the protection backup time, no action is required.

40 Fault clearing times of the backup protection system (it can have more than one step), activated if the main protection system fails. Thus, backup time has to be longer than base clearing time.

Figure 25: Workflow to perform transient stability studies

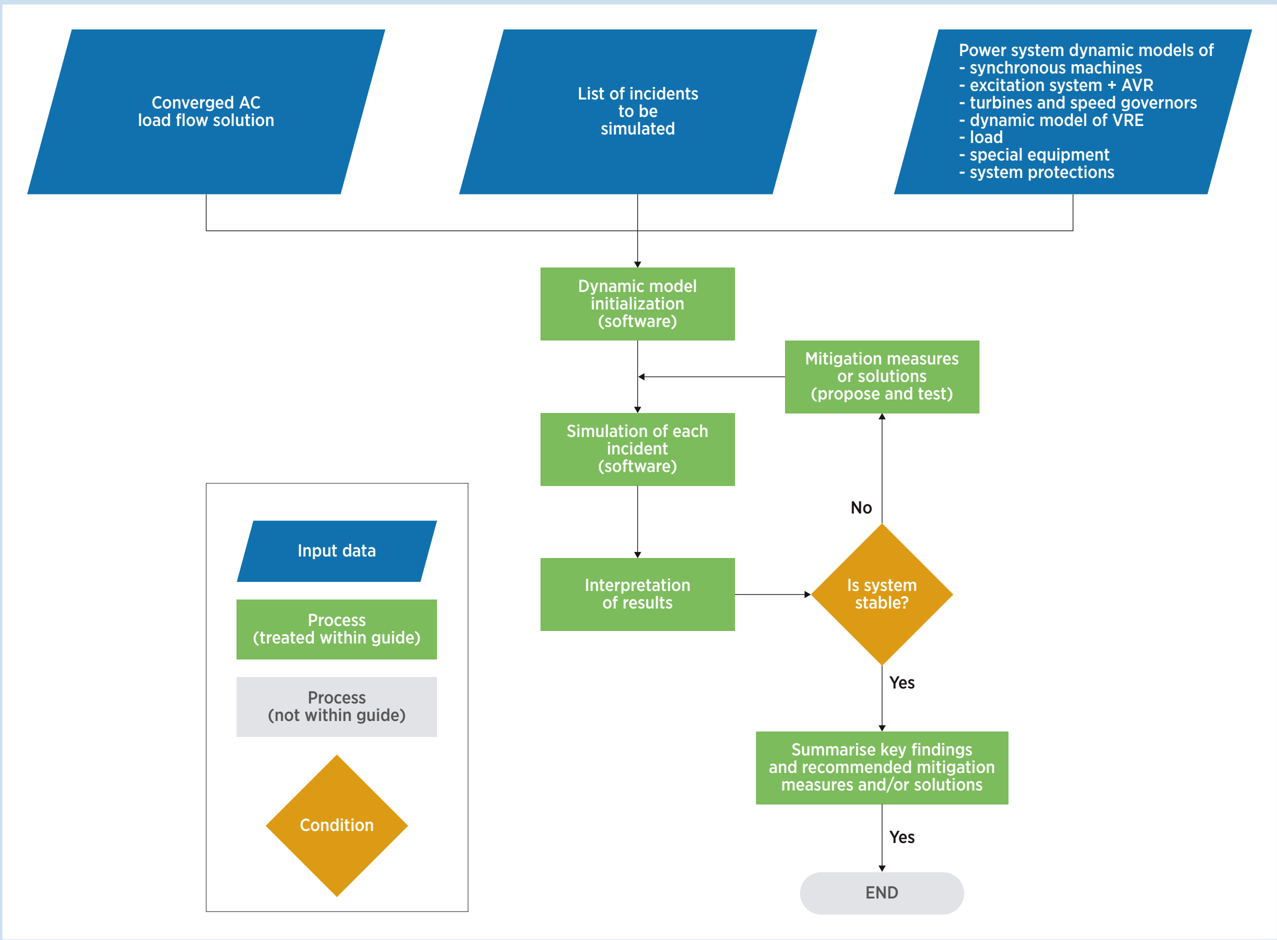
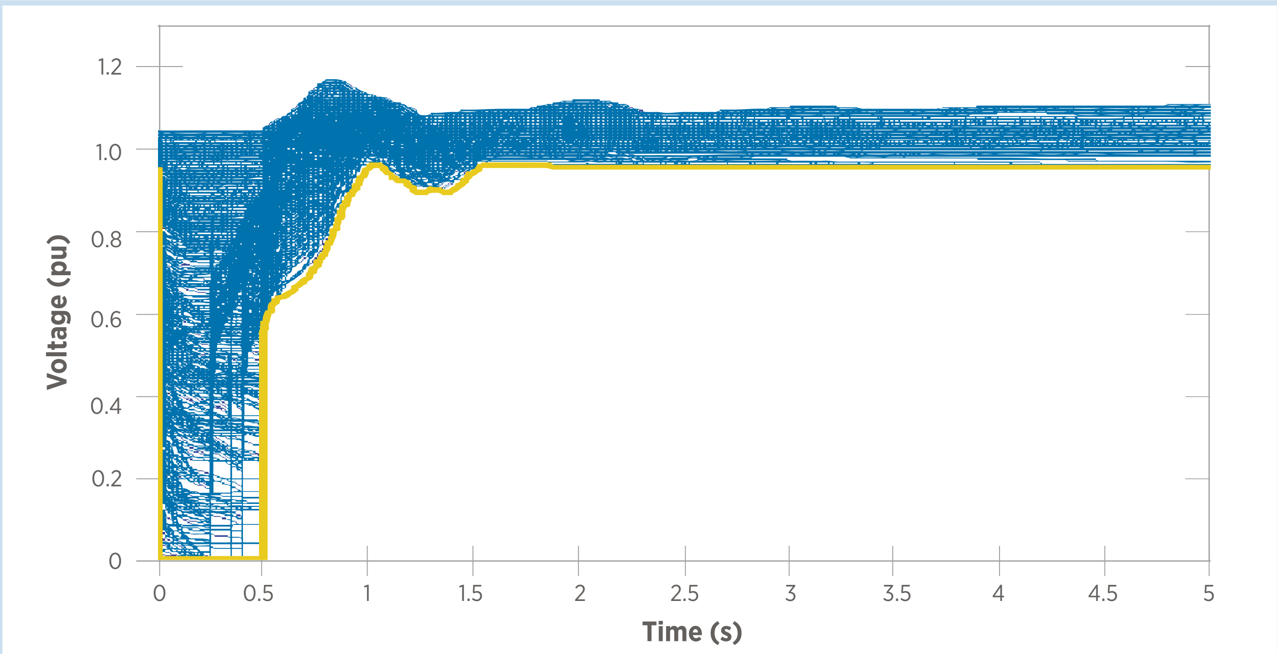


Figure 26: Transient stability simulation results for the determination of system's LVRT characteristic



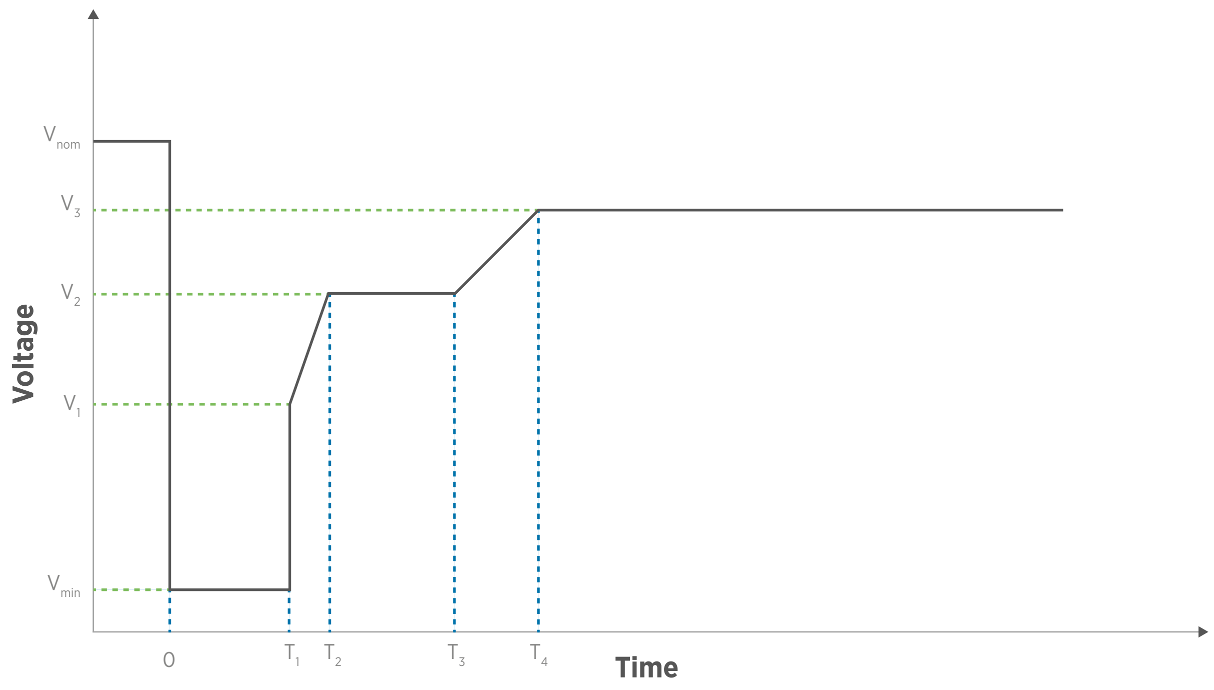
Once the low-voltage envelope was extracted from the analysis of the different voltage curves, the following LVRT requirements were recommended to be implemented in the grid code (see Figure 27).

A second example of transient stability analysis relates to an operational planning study done for the Canary Islands (Merino et al., 2012). The aim of this study was to define the best procedure over the active elements in the system to guarantee that the operational criteria are met during and after the contingency. The main conclusions of this study are the following:

- When wind power is the only generation source, system stability during critical faults cannot be maintained (see Figure 28).

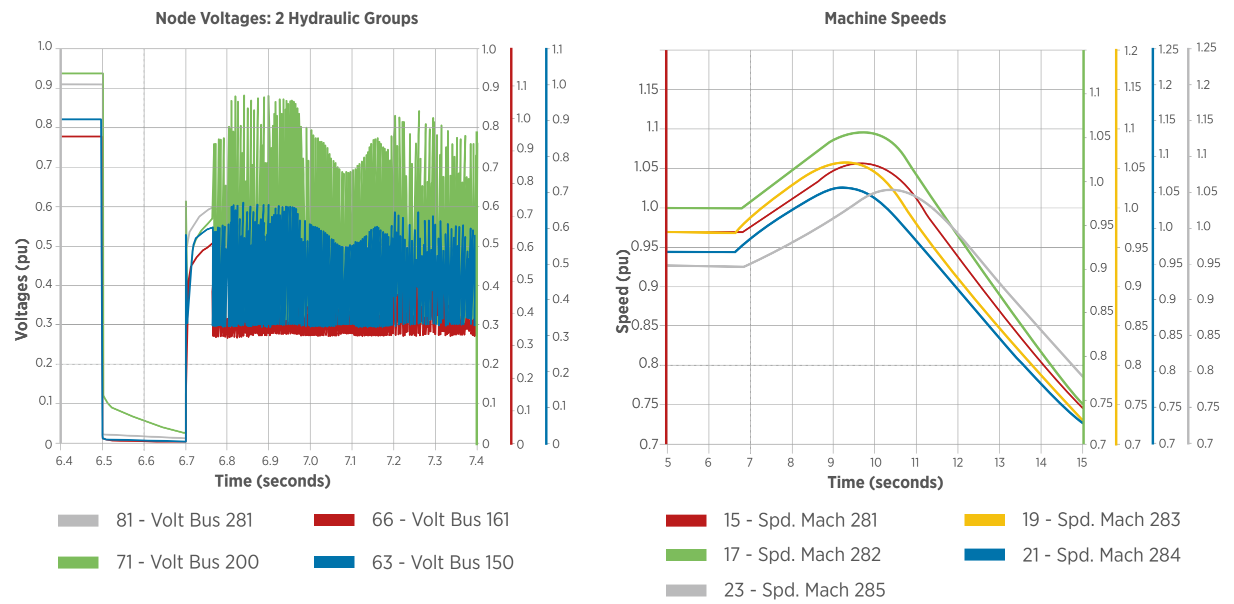
- To allow maximum wind production, some hydraulic units must be set to run as synchronous condensers (with minimum level of water consumption), as shown in Figure 29.

Figure 27: Transient stability simulation results: recommended LVRT characteristic



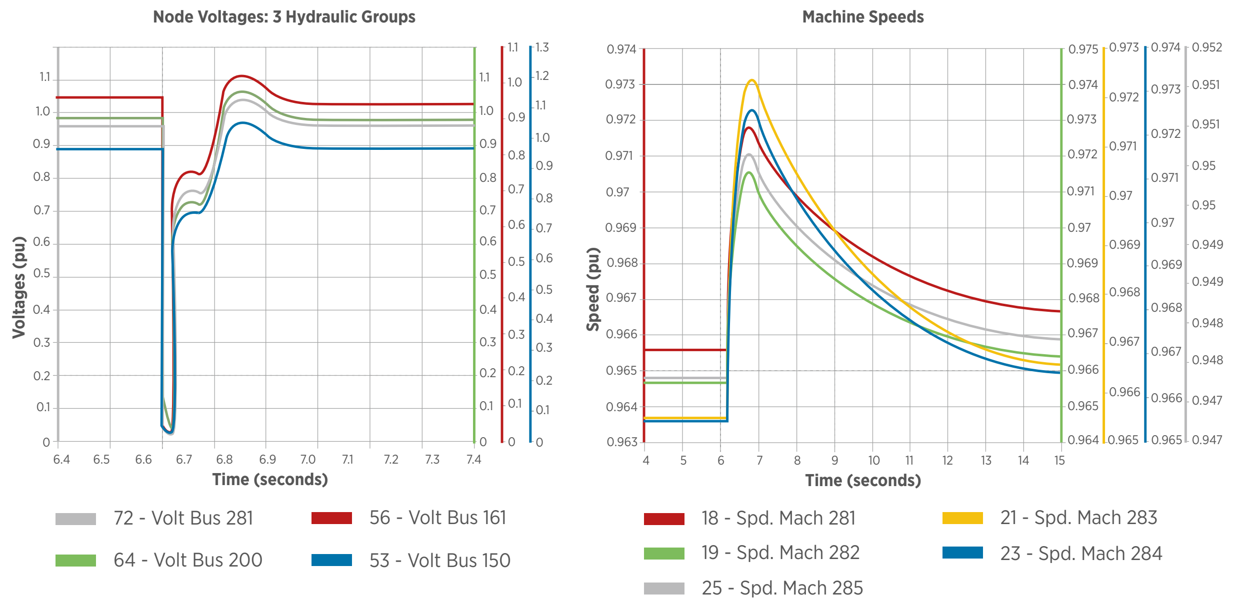
Time in seconds				Voltage in pu			
T_1	T_2	T_3	T_4	V_1	V_2	V_3	V_{min}
0.5	0.7	1.3	2.0	0.45	0.65	0.85	0.0

Figure 28: Transient stability simulation results: insufficient conventional units online leading to loss of stability



Source: Merino et al., 2012.

Figure 29: Transient stability simulation results: sufficient conventional units online



Source: Merino et al., 2012.

7.2. Frequency stability

Frequency stability refers to the ability of a power system to regain stable system frequency following a severe system disturbance resulting in a significant active power imbalance between generation and load (IRENA, 2015a).

If frequency deviations are severe enough, some generating units may disconnect, further aggravating the frequency excursion and progressively causing other disconnections. This process, if not managed, can lead to blackout of the system. Defence plans, including UFLS, and frequency control mechanisms are in place to prevent this eventuality. For more details on defence plans, see Chapter 8.

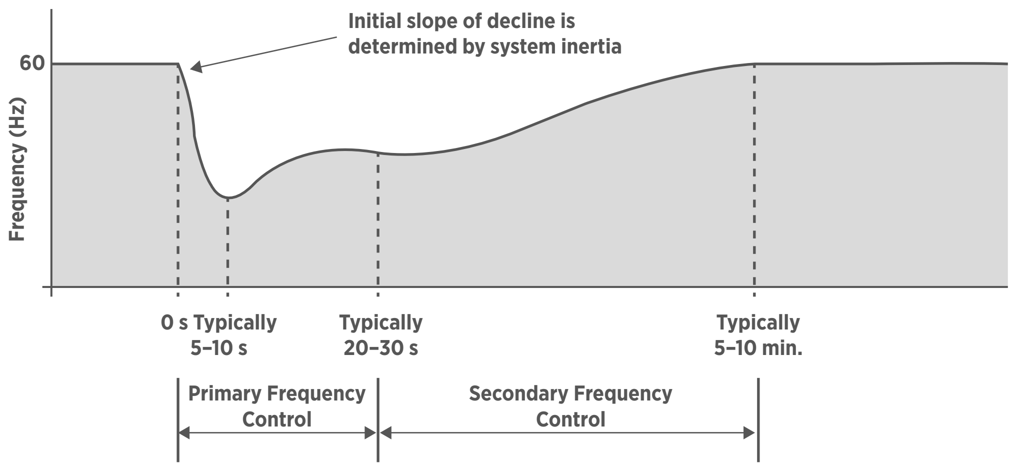
Frequency stability in power systems is impacted mainly by three aspects: inertial response, primary frequency response and secondary frequency control (automatic generation control, when available). Figure 30 shows the temporal breakdown of the different responses.

The ***inertial response*** is the immediate response to active power unbalance that causes frequency to deviate from its nominal value, such as the loss of a generating unit, significant sudden load variation or power generation fluctuations due to the widespread deployment of VRE sources. Inertial response is important in order to limit the rate of change of frequency (ROCOF) after a disturbance, which can lead to avoiding the activation of UFLS or complete system blackout. Synchronous generators naturally provide inertial response from stored kinetic energy in their rotating mass.

VRE sources such as wind turbines and solar PV arrays connect to the grid via power electronics-based converters, which decouples the primary power generation from grid frequency, thus not contributing to the system inertia. However, modern VRE power plant design enables the implementation of synthetic inertia by means of advanced control functions. Figure 31 illustrates the frequency behaviour following the same incident for different values of system inertia.

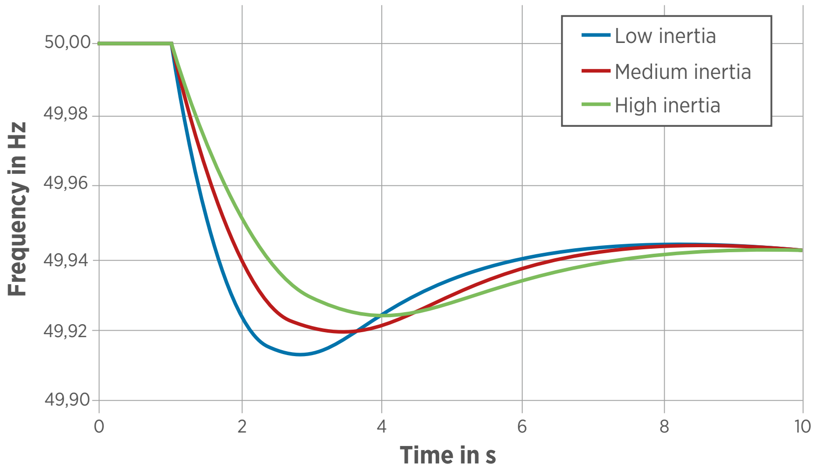
The ***primary frequency response*** follows the inertial response. It is the action by governor controls to change the power output to balance generation and load and to ensure that system frequency returns to a stable steady-state value following a disturbance. If the frequency deviates too much from its nominal value (due to the severity of the disturbance or the reduced inertia of the system), the stability of the grid is at risk. UFLS relays can trigger load tripping, and generators can be tripped by their over-/under-speed relays.

Figure 30: Frequency response following a load/generation unbalance



Source: NREL, 2014.

Figure 31: Frequency behaviour for different system inertia



Source: IRENA, 2015a.

The primary frequency response is intrinsically related to the amount of available primary reserve and the droop characteristic of the governors. VRE power plants respond better to grid frequency increases, which require a reduction in power generation. However, VRE can also provide up-regulation reserves under the following conditions: when operating below maximum instantaneous available power (de-rated operation) or when equipped with local energy storage such as batteries.

The ***secondary frequency control*** is used to continuously balance the system and to restore the frequency to its nominal value by acting at the active power set-point of the generating units. This control is usually provided by conventional power plants only. It can be implemented as an automatic generation control system or be performed manually by the system operator given that it is not directly related to the system stability, but rather used to restore the frequency to its nominal value after the action of the primary frequency control.

A detailed description of frequency stability and its importance for small-island power systems is given in Sigrist et al. (2016).

Study results and evaluation criteria

A frequency stability study usually has four main objectives:

- evaluate the adequacy or perform the adjustment of UFLS schemes, automatic generation control performances and primary reserve requirements;
- evaluate the maximum transient frequency deviation in order to determine the minimum inertia requirement;
- evaluate if the steady-state frequency deviation for a given disturbance lies within the range specified in the grid-code;
- evaluate the activation of active power reduction schemes of VRE following over-frequency phenomena (or to perform the adjustment of these schemes).

Frequency stability issues may occur in different time frames, as follows (M.P.E. GmbH, 2013):

- ***Few seconds:*** transient frequency drop defined by system inertia and performance of primary reserves.
  Potential issues:
  - Too-low system inertia leading to large and fast frequency drops
  - Slow primary reserve response, compromising frequency recovery.

  Contribution to frequency control:
  - All synchronous and directly coupled asynchronous generators and motors connected to the system.

- ***10 to 30 seconds:*** steady-state frequency deviation defined by the primary frequency control.
  Potential issues:
  - Insufficient primary reserves
  - Poor technical performance of primary reserves (activation time too slow).

  Contribution to frequency control:
  - All generators participating in the primary frequency control.

- ***5 to 10 minutes:*** restoration of system frequency to its nominal value.
  Potential issues:
  - Insufficient secondary reserve
  - Poor technical performance of secondary reserves (activation time too slow).

  Contribution to frequency control:
  - All generators participating in the secondary frequency control.

The evaluation criteria for frequency stability studies are the following:

- adequacy of UFLS schemes and primary reserve;
- maximum transient frequency deviation versus minimum inertia requirement;
- steady-state frequency deviation within the range specified in the grid code;
- activation of active power reduction schemes of VRE following over-frequency phenomena.

Methodology to perform the study

The development of a dynamic model of the small-island power system is required to perform a frequency stability study. As mentioned before, a convergent load flow solution complying with all operational criteria must be available beforehand to allow for power system dynamics simulation.

The following events are usually simulated in frequency stability studies:

- loss of the largest non-VRE generating unit,

- sudden increase in the load,

- sudden decrease in the load (usually the tripping of the largest load in the system),

- sudden variation in VRE generation (the magnitude of this sudden VRE production variation is determined according to what is presented in Section 4.2 about operating reserves).

The recommended simulation duration for frequency stability analysis depends on the characteristics of the generating unit governors. A typical range for performing these simulations is between 60 and 300 seconds. Once the simulations are finished, verification of the different criteria presented previously must be performed.

To assess the impacts of VRE penetration, the most critical scenarios from the point of view of system integration of VRE must be analysed. These scenarios are specified in the topic selection of scenarios for network studies in Section 3.3.

Table 17 provides a list of measures that can be adopted to improve frequency stability at each planning stage.

Table 17: Potential issues and solutions at the different planning stages for frequency stability studies

Expansion planning	Operational planning
• In case frequency collapse is detected due to the lack of operating reserves, the following actions may be foreseen: increase frequency regulation capability of the system by requiring VRE sources to contribute to the primary reserve and/or deployment of energy storage for frequency control purposes. • In case large frequency drops are detected due to the lack of inertia, resulting in the activation of UFLS schemes, the following actions may be foreseen: impose the implementation of virtual inertia function to the VRE power plants or deployment of energy storage for frequency control purposes.	• In case frequency collapse is detected due to the lack of operating reserves or inadequate UFLS schemes, the following actions may be foreseen: generation re-dispatch (additional conventional units dispatched at lower output level to increase primary reserves) and/or improvement of UFLS settings. • In case large frequency drops are detected due to the lack of inertia, resulting in the activation of UFLS schemes, the following actions may be foreseen: synchronise additional conventional generating units to increase system inertia (requires generation re-dispatch) and/or adjustment of UFLS settings. Methods for re-adjusting UFLS settings can be find in Sigrist et al. (2016)

Analysis of results and next steps

The phenomena that are typically observed in a frequency stability study are presented as follows:

- Load/generation imbalance will lead to frequency deviations from its nominal value. Usually, synchronous generators will accelerate following a sudden load reduction during the fault, and rotor angle will increase. Following a sudden load increase or trip of a generating unit, synchronous generators will decelerate.

- Generating units will experience different transient local frequency. However, once a post-event steady-state condition is reached, the frequency will be the same at every point of the network (except in the case of network split, in which each sub-network will have its own post-event frequency).

- The system is stable if a steady-state frequency value within the acceptable range (no need for UFLS intervention) is obtained after the transient period and the voltages return to a post-fault steady-state operating point.

The following aspects are typically observed in a frequency stability study (M.P.E. GmbH, 2013):

- Reduced system inertia due to the integration of VRE sources results in faster initial frequency rate of change and deeper transient frequency drops following the tripping of a generating unit or a sudden reduction in VRE generation.

- If the highest VRE generation variability results in power fluctuations higher than the tripping of the largest conventional generating unit, additional amounts of primary and secondary reserves are required. If deployment of additional reserves is not possible, higher amounts of load shedding due to UFLS schemes activation can be expected.

- High VRE penetration levels might lead to the need to require VRE sources to contribute to the operating reserves.

Depending on the objective of the frequency stability study, different measures can be applied to solve possible problems identified. For example, if the objective of the study is to analyse the future expansion of the system (expansion planning), problems might be solved by specifying new investments in balancing means (electricity storage, virtual inertia, etc.). However, if the study is intended for short-term operation (operational planning), investments in new equipment are usually not possible. In this case, operational measures such as generation re-dispatch (including VRE curtailment), review of governor settings and optimisation of UFLS schemes must be envisaged. For more details on the relation between the study results and the solutions to be applied, see Chapter 9.

Workflow to perform the study

The workflow on how to perform frequency stability studies is same as the workflow in Figure 25.

Examples of study results

This section synthesises the conclusions obtained from frequency stability studies performed under a solar power integration study on the island of Mahé in the Seychelles (Brown et al., 2016).

The frequency stability studies for different target years were aimed at identifying the limits of solar PV integration for the system. The main conclusion of the study was that the conventional units that remained connected to the system were able to provide adequate primary frequency control support in all studied scenarios. Figure 32 shows the frequency behaviour of the system after the sudden loss of 4 MW of PV generation on Mahé.

A second example of frequency stability study relates to a project aimed at studying the integration of wind and solar power in the island of Barbados (GE Energy Consulting, 2015). In this study, the frequency stability analysis task was aimed at analysing the frequency regulation capability of the Barbados Light & Power Company grid. The main conclusion of the study was that an automatic generation control system needed to be implemented to regulate the grid frequency following the fluctuation of wind and solar PV power production, as shown in Figure 33 and Figure 34.

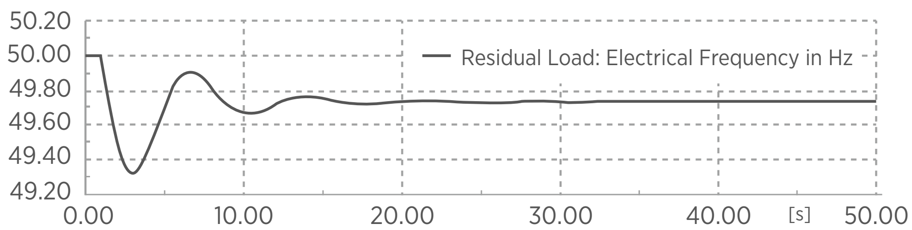
Another comprehensive example of a frequency stability study can be found in Kumar et al. (2017).

7.3. Voltage stability

Dynamic voltage stability is the ability of a power system to maintain steady acceptable voltages at all busbars in the system under normal operating conditions and after being subjected to a disturbance (Kundur, 1994). Voltage instability occurs when a disturbance (fault, increase in load demand or change in system condition) results in progressive and uncontrolled voltage drop (voltage collapse).

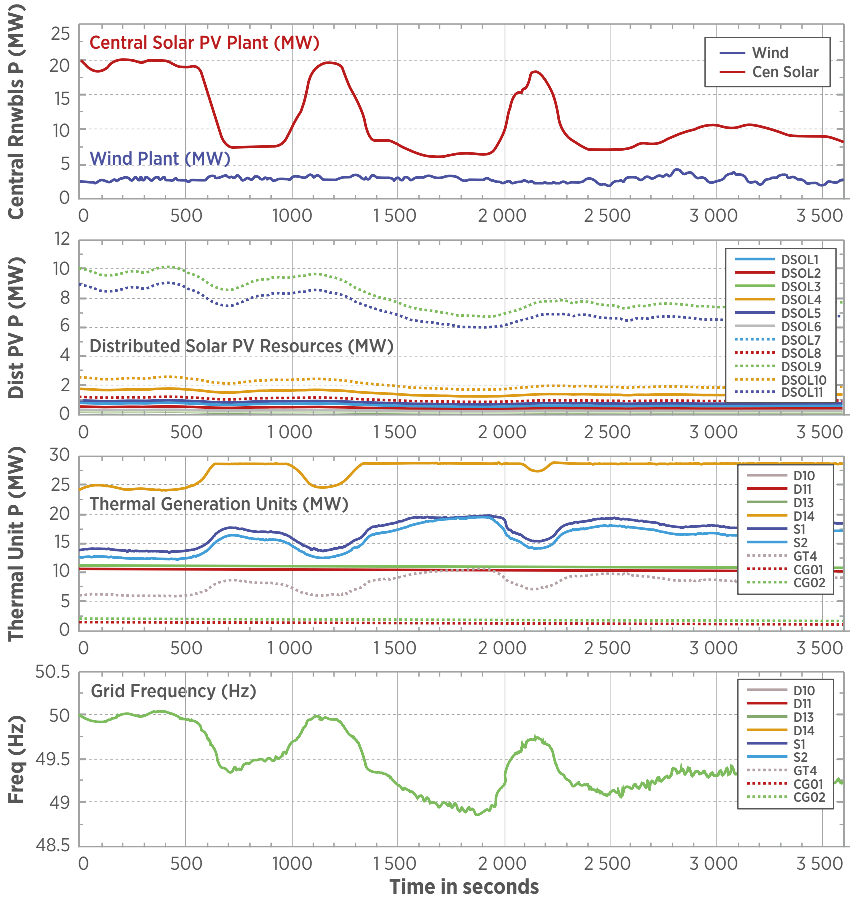
The main factor that leads to voltage instability is the inability of the power system to meet the reactive power demand. Instability may occur when a disturbance leads to an increased reactive power demand that exceeds the reactive power capability of the generating units.

Figure 32: Frequency behaviour of the system after the sudden loss of 4 MW of PV generation on Mahé



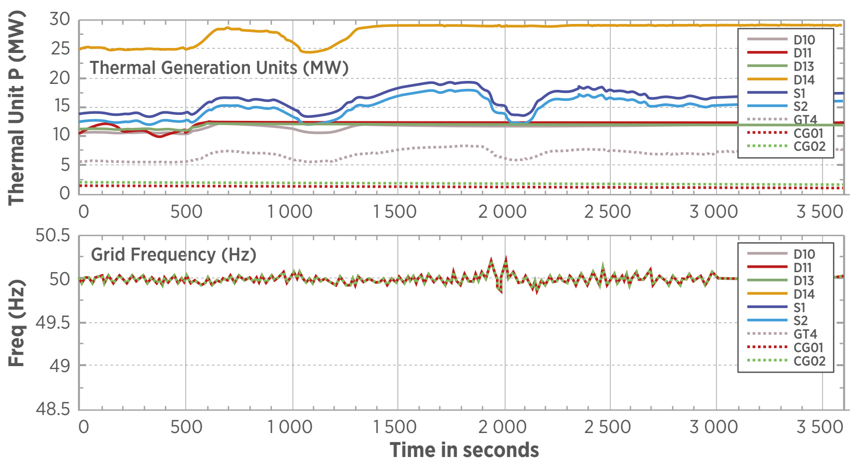
Source: Brown *et al.,* 2016.

Figure 33: Grid frequency performance without automatic generation control



Source: GE Energy Consulting, 2015.

Figure 34: Grid frequency performance with automatic generation control



Source: GE Energy Consulting, 2015.

Voltage instability is unlikely to happen in small-island power systems without VRE due to the short electrical distances of the network (IRENA, 2015a). However, because a significant amount of synchronous generators might be disconnected from the grid during times of high VRE penetration, VRE integration can have a negative impact on voltage stability due to the following (M.P.E. GmbH, 2013):

- VRE sources can have lower reactive power provision capability than conventional generating units based on synchronous machines.

- Reactive power must be locally provided. If the VRE sources are located relatively far from the load, it might be possible that the reactive power capacity of the VRE sources cannot be made available at the location where it is actually needed.

- If an important share of VRE sources is deployed in form of distributed generation, the reactive power capability of these sources will not be available for providing voltage support in medium- or high-voltage levels.

Study results and evaluation criteria

A voltage stability study usually has three main objectives:

- evaluate if a voltage collapse is likely to happen in part of or all of the network

- assess the adequacy of over-/under-voltage load shedding (OVLS/UVLS) schemes

- analyse if over- or under-excitation limiters of synchronous generators are activated.

The evaluation criteria for voltage stability studies are the following:

- voltage collapse in part of or all of the network

- adequacy of OVLS/UVLS schemes

- steady-state voltage magnitudes within the range defined in the grid code

- activation of over/under-excitation limiters of synchronous generators.

Methodology to perform the study

To reach these objectives, the following events are usually simulated:

- short circuit in network elements (lines, cables, transformers, etc.) cleared in base time

- small variations in the VRE power generation

- small variations in the load.

The study period of interest for voltage stability analysis is larger than for transient and frequency stability due to the slower nature of the voltage instability phenomena. A typical range for performing these simulations is between 5 to 10 minutes.

To assess the impacts of VRE penetration, the most critical scenarios from the point of view of system integration of VRE must be analysed. These scenarios are specified in the topic selection of scenarios for network studies in Section 3.3.

Analysis of results and next steps

The phenomena typically observed in a voltage stability study are presented as follows:

- Faults will lead to transient voltage depletion and restrictions on power transfer.

- Induction motors (load) slip will increase during the fault.

- The system is stable if after fault clearance (by tripping the faulted element or due to the temporary nature of the fault), the voltages transiently recover to values close to the nominal ones and return to a post-fault steady-state operating point within the specified ranges.

Table 18: Potential issues and solutions at the different planning stages for voltage stability studies

Expansion planning	Operational planning
In case voltage collapse is detected due to the lack of reactive power support, the following actions may be foreseen: investment in network reinforcement and/or investment in new reactive power compensation means (reactor/capacitor banks, static VAR compensators, etc.).	In case voltage collapse is detected due to the lack of reactive power support, the following actions may be foreseen: generation re-dispatch (additional conventional units dispatched at lower level or closer to the load centres to increase reactive power support) and optimisation of the reactive power compensation means.

Depending on the objective of the voltage stability study, different measures can be applied to solve possible problems identified. For example, if the objective of the study is to analyse the future expansion of the system (expansion planning), problems might be solved by specifying new investments in reactive power compensation means (reactor/capacitor banks, static VAR compensators, etc.). However, if the study is intended for short-term operation (operational planning), investments in new equipment are usually not possible. In this case, operational measures such as generation re-dispatch (including VRE curtailment) and optimisation of reactive power compensation means must be envisaged. For more details on the relation between the study results and the solutions to be applied, see Table 18, which provides possible measures that can be undertaken to improve voltage stability in the planning stages.

Workflow to perform the study

The workflow on how to perform voltage stability studies is similar to the one given in Figure 25.

Relationship between different stability phenomena

Even if power system stability phenomena can be classified in different categories, it would be a mistake to consider analysing each type of stability phenomena independently from another. In the case of small-island power systems, even a small disturbance can result in a cascading effect of other events. In this case, a single stability phenomenon can trigger a different one.

For instance, a dynamic stability study on the system of a small Pacific island[41] has analysed the issues arising from the starting of a defective induction motor. Initially, the diesel generator had to increase its reactive power output to compensate for the voltage drop produced by the abnormal starting current (like a short circuit) of the motor (with locked rotor). However, the low voltage caused the solar plants to trip, due to limited FRT capability. At that point, the generator started increasing its power output as well to compensate for the lost solar generation, but the response was limited by the high reactive power output to compensate for the system's low voltage. When the motor tripped, voltage rose and the diesel generator could stabilise the frequency.

In other words, several types of stability phenomena may co-exist simultaneously and appear intermingled (M.P.E. GmbH, 2013). This highlights the importance of, when performing a system stability study, not being limited to the analysis of a single stability type. Table 19 provides a summary of the methodology for system stability analysis.

7.4. References for further reading

- Power system stability and control: Kundur (1994); Kundur et al. (2004)
- Power system voltage stability: Taylor (1993)
- Standard dynamic models of excitation system and automatic voltage regulator: IEEE Power Engineering Society (2005)
- Standard dynamic models of turbines and speed governors: IEEE Power & Energy Society (2013)
- Standard dynamic models of wind turbines: IEC (2014).

41 Composed of four 500 kW generators in a single power plant plus about 52 kW of solar power plants connected to the grid.

Table 19: Summary of system stability analyses

Requirement	Description
Methodology	• Develop the dynamic model of the system. • Perform load flow computation for the selected scenario. • Perform system stability simulations: ◦ Transient stability (three-/bi-/single-phase fault) ◦ Frequency stability (load increase/decrease, disconnection of generating units) ◦ Voltage stability (three-/bi-/single-phase fault, load increase/decrease, disconnection of generating units). • Analyse the results.
Scenarios	See Section 3.3: selection of scenarios for network studies.
Model requirements	Same as presented in Table 12, as well as: • Dynamic model of the different system equipment (generators, loads, on-load tap changers, etc.) • Model of protection equipment • Simulation events according to the type of stability to be studied.
Input data	Same as presented in Table 12, as well as: • Dynamic model of generating units and associated regulating devices (synchronous machines, asynchronous machines, inverters, automatic voltage regulator, PSS, turbine, speed governor, etc.) • Dynamic data of special network equipment (on-load tap changer, phase-shift transformer, FACTS, etc.) • Settings of machine and network protection relays • Logic and settings of special protection schemes • Dynamic load models • Grid code requirements.
Criteria for the analysis of results	• Transient stability: ◦ Loss of synchronism of a machine or group of machines ◦ Critical clearing times higher than protection fault clearing times. • Frequency stability: ◦ Adequacy of UFLS schemes and primary reserve ◦ Maximum transient frequency deviation versus minimum inertia requirement ◦ Steady-state frequency deviation within the range specified in the grid code ◦ Activation of active power reduction schemes of renewable energy sources following over-frequency phenomena. • Voltage stability: ◦ Voltage collapse in part of or all of the network ◦ Adequacy of OVLS/UVLS schemes ◦ Voltage magnitudes within the range defined in the grid code ◦ Activation of over/under-excitation limiters of synchronous generators.

Table 19: Summary of system stability analyses (cont.)

Requirement	Description
Outcomes of the simulation	• Transient stability margin of the system (CCTs) • Adequacy of UFLS and OVLS/UVLS protection schemes • Adequacy of reactive power/voltage control means • Adequacy of primary reserve levels (including the reserves provided by controlled load shedding schemes).

Interpretation of the simulation results	• Transient stability (Bayliss et al., 2012):
	  ◦ Faults will lead to transient voltage depletion and restrictions on power transfer. Usually, synchronous generators will accelerate during the fault and rotor angle will increase.
	  ◦ Synchronous generating units closest to the fault will experience the greatest load reduction and will accelerate faster than units electrically far from the fault.
	  ◦ For the same amount of loss load during the fault, synchronous generators with lower inertia will accelerate more quickly. Generators within the same power plant may remain in step with each other while diverging from the apparently higher inertia grid infeed.
	  ◦ Induction motor (load) slip will increase during the fault.
	  ◦ The system is stable if after fault clearance (by tripping the faulted element or due to the temporary nature of the fault), stability will be indicated by a tendency for the rotor angle swings to be arrested, for voltages and frequency to return to a post-fault steady-state operating point and for induction motor slips to return to normal load values.
	• Frequency stability:
	  ◦ Load/generation imbalance will lead to frequency deviations from its nominal value. Usually, synchronous generators will accelerate following a sudden load reduction during the fault and rotor angle will increase. Following a sudden load increase or trip of a generating unit, synchronous generators will decelerate and the rotor angle will also increase.
	  ◦ Generating units will experience different transient local frequencies. However, once a post-event steady-state condition is reached, the frequency will be the same in every point of the network (except in case of network split, in which each sub-network will have its own post-event frequency).
	  ◦ The system is stable if a steady-state frequency value within the acceptable range is obtained after the transient period and the voltages return to a post-fault steady-state operating point.
	• Voltage stability:
	  ◦ Faults will lead to transient voltage depletion and restrictions on power transfer.
	  ◦ Induction motor (load) slip will increase during the fault.
	  ◦ The system is stable if after fault clearance (by tripping the faulted element or due to the temporary nature of the fault), the voltages transiently recover to values close to the nominal ones and return to a post-fault steady-state operating point within the specified ranges.

Examples of commercial software tools	• PowerFactory (DIgSILENT GmbH), ETAP (ETAP), EUROSTAG (Tractebel), NEPLAN (NEPLAN AG), PSLF (GE), PSS/E (Siemens PTI), PowerWorld Simulator (PowerWorld Corporation).

8. NETWORK STUDIES FOR SYSTEM PLANNING IN SMALL ISLAND DEVELOPING STATES: SPECIAL STUDIES

This chapter describes two special studies that are relevant for planning small-island power systems for the integration of VRE sources:

- defence plans
- grid connection studies.

These studies are based on a combination of the studies presented previously, aimed at specific purposes. More details on the mapping and organisation of the technical studies are presented in Chapter 3. A detailed description and methodology of these types of studies is given in the following sections.

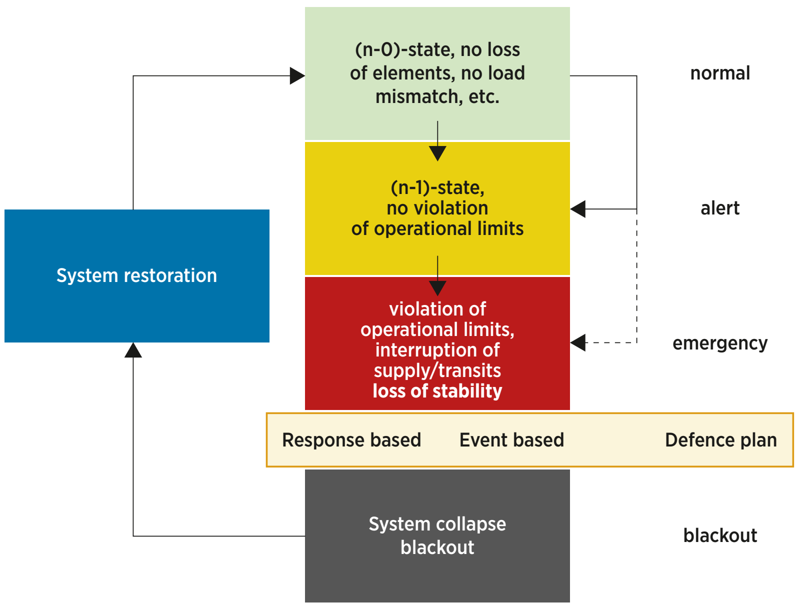
8.1. Defence plans

In general, power systems are planned, built and operated to withstand a predefined set of credible contingencies (normative incidents). A credible contingency is a contingency or a fault that has been specifically foreseen in the planning and operation of the system, and against which specific measures have been taken to ensure that no serious consequences would follow its occurrence (ENTSO-E, 2010). In particular, the load demand supply should not be affected within given limits by the predefined set of normative incidents.

A defence plan can be defined as a set of co-ordinated measures aimed at maintaining the integrity of the system in case abnormal system conditions result from non-normative incidents (ENTSO-E, 2014). Figure 35 depicts the role of a defence plan on the power system operating states[42]. The definition of each different power system state is given in Section 6.2.

The objective of defence plan studies is to set up technical recommendations and rules for manual or automatic actions to manage critical system conditions to prevent it from the loss of stability and cascading effects leading to blackouts (focus on the emergency state).

Figure 35: Defence plan overview



Source: Grebe, 2012.

42 Operation of power systems is classified into power system operating states to facilitate the analysis of power system security and the design of appropriate control systems.

Because small-island power systems are very sensitive to disturbances due to the limited extent of the system and the introduction of VRE generation, such kinds of protection schemes can be envisaged in order to increase system security and avoid major blackouts.

For small-island power systems, a focus on out-of-step relays, UFLS schemes and automatic generation re-dispatch is recommended.

A defence plan is typically composed of Special Protection Schemes (SpPS) and System Protection Schemes (SyPS). SpPS are employed to counteract violation of operational criteria and instability phenomena following a normative contingency so that the system recovers from an emergency to an alert state. SyPS are employed to counteract system instability following non-normative contingencies so that the system recovers from a system collapse or blackout tendency to a stable operating condition (Grebe, 2012).

SpPS and SyPS comprise, but are not limited to, the following types of protection schemes:

- Under-frequency load shedding (UFLS)
- Over-/under-voltage load shedding (OVLS/UVLS)
- Special measures such as generation re-dispatch
- Automatic connection/disconnection of reactive power compensation equipment
- Instructions for transformer tapping
- Out-of-step protection.

8.2. Grid connection studies

During the development phase of new generation assets, whether for a conventional unit or VRE, a grid connection study must be carried out by the project developer (whether the utility itself or a private stakeholder). This study is usually divided into two parts:

- ***Grid impact study:*** aims to verify whether the existing electricity system is capable of integrating the new generating unit.
- ***Grid code compliance study:*** aims to verify whether the new installation is compliant with the various grid code requirements.

Both studies consist of static and dynamic stability simulations of the system, which are used to verify various technical requirements. For some aspects, the distinction between a grid impact and a grid code compliance study is ambiguous. It is hard to attribute certain technical requirements to the former or the latter. The chosen approach in this kind of situation is to follow the most practical solution in terms of project management:

- ***Grid impact study:*** is often part of the (pre)feasibility study of a new generation asset. Some important conclusions for the project developer are drawn based on certain calculations. Perhaps the most important aspect in terms of project development is the assessment of the evacuation capacity[43]. The various calculations of the grid impact study determine the evacuation capacity at the proposed point of connection. If the total power of the new generation cannot be evacuated, another point of connection must be sought or the scope of the project must be revisited.

- ***Grid code compliance study:*** takes place immediately after the grid impact study, or in a later stage, when the detailed design of the new power plant is completed.

Note that grid connection studies do not consist of a different type of study or simulation from those presented in previous sections. Grid connection studies are a combination of the static and dynamic stability studies presented previously but with a very specific objective: to analyse the behaviour of the new equipment rather than the complete behaviour of the system. For this reason, more detailed information on the studied project is required with respect to system-level studies.

43 Maximum amount of power that can be injected into the grid at a given connection point, compliant with security criteria.

9. SOLUTIONS TO INCREASE VARIABLE RENEWABLE ENERGY PENETRATION IN SMALL ISLAND DEVELOPING STATES

This chapter presents possible solutions to address the technical constraints that may be identified based on the technical studies presented in previous chapters. It investigates the different possible measures that a small island developing state could implement to increase the VRE hosting capacity of its power system and reach targeted integration objectives.

As noted through this document, one should not think about an absolute VRE penetration limit. Grid integration studies conducted to date have indicated that a technological solution nearly always exists for increasing the VRE penetration level that can be adopted at some cost (Cochran et al., 2015). These solutions can be categorised as:

- ***Infrastructure investments***, including diversification of VRE installations, flexible thermal generation, electricity storage, conventional transmission and distribution grid reinforcements, interconnection with neighbouring systems, distribution automation, and smart transmission and distribution grids.

- ***Operational measures***, including demand-response programmes, adapted generation dispatch and control strategies, adapted defence plans, automatic power controller and network monitoring, and accurate VRE forecasts.

- ***Technical requirements on VRE generators'*** capabilities that could be imposed by grid codes to ensure stable operation of the system.

These different solutions have been extensively covered by the literature in recent years. Dedicated IRENA reports are also addressing some of them, including:

- Battery Storage for Renewables: Market Status and Technology Outlook (IRENA, 2015g)
- Renewables and Electricity Storage: A Technology Roadmap for REmap 2030 (IRENA, 2015h)
- Smart Grids and Renewables: A Cost-Benefit Analysis Guide for Developing Countries (IRENA, 2015b)
- Scaling Up Variable Renewable Power: The Role of Grid Codes (IRENA, 2016b)

The purpose of this chapter is not to reproduce the detailed information available in these reports, but rather to discuss the applicability of the different solutions to the specific issue of VRE integration in the power systems of SIDS.

Table 20: Solution summary table

VRE integration challenges addressed	Which technical VRE integration challenges are addressed by the solution? A distinction is made between the challenges for which the solution has significant impact and those for which it has only a moderate impact.
Integration in technical studies	Which planning studies can be impacted by the solution and how to integrate the solution in the study?
Relation and synergies with other solutions	With which other solutions can it be combined to produce synergistic effects? Are other solutions required to enable it? Is it in competition or redundant with other solutions?
Applicability to SIDS	What is the degree of applicability of the solution to SIDS? A qualitative assessment is provided, from low to high applicability, depending on aspects such as cost, maturity, logistics, institutional framework, etc.
VRE penetration threshold	Qualitative penetration level (referring to maximum instantaneous penetration), from low to high, at which the solution becomes applicable or interesting given the technical challenges addressed. The same approximate qualitative ranges are used as those presented in Section 3.4, *i. e.*, low, medium and high* (IRENA, 2013).

* Low (0–15%), medium (10–30%) and high (20–100%) shares of the total instantaneous load.

For each solution in this chapter, summary tables as described in Table 17 present details on: the VRE integration challenges addressed, its integration in technical studies, its relation and synergies with other solutions, its applicability to small-island power systems and the VRE penetration at which the solution becomes applicable.

The final section provides a comparative synthesis of the different solutions and can be used as a guide to select the most appropriate ones. Generally, a mix of solutions will be required to reach high VRE penetration. While some individual solutions (such as electricity storage) enable addressing a broad range of technical challenges of VRE integration, combining several alternative solutions might sometimes lead to lower overall costs. Careful cost-benefit analysis of the different combination of options is therefore important (although not treated in detail within this guide). This makes it possible to implement the feedback loop proposed in most of the technical studies in order to solve the identified technical issues.

9.1. Infrastructure investments

This section discusses possible infrastructure investments that can be applied to facilitate VRE integration in SIDS. These solutions generally involve significant investment costs and need to be planned sufficiently in advance due to the lead time for installation. They therefore should be considered when conducting the capacity expansion planning of the small island developing state, targeting time horizons that account for the required lead time of new installations.

Diversification of VRE installations

Diversifying the types of VRE by mixing solar PV with wind power or run-of-river hydropower allows for smoothing the variability of the total VRE generation. Spreading the locations of the different VRE generators over large geographical areas also produces a smoothing effect.

This smoothing is favourable to avoid intraday flexibility and stability issues related to the sudden variation of VRE power output. De-correlating the power outputs of VRE generators has a positive effect on adequacy by allowing higher effective load carrying capacity (ELCC). Moreover, the geographical diversification also reduces operational challenges related to the concentration of VRE in certain portions of the grid.

Such diversification decisions can be made (or even optimised) at the stage of VRE project definition and selection within the generation capacity expansion plan. It is also possible to implement it as feedback loop from the technical studies presented in this guide if it appears that a given generation expansion scenario does not satisfy some technical criteria.

Table 21 presents further details on the diversification of VRE installations as a solution for VRE integration and its applicability to SIDS.

Table 21: Solution summary – diversification of VRE installations

VRE integration challenges addressed	Significant impact: generation adequacy, intraday flexibility, stability, static thermal/ voltage grid limits. Moderate impact: short circuits and protections, power quality.
Integration in technical studies	Influences the types, output profiles and locations of VRE generators in all technical studies. Feedback to generation expansion planning.
Relation and synergies with other solutions	Requires more complex management systems compared to single technology or location for VRE.
Applicability to SIDS	Low-to-medium applicability. In small islands geographical spread is more difficult to achieve. Applicability also depends on availability of land and renewable energy sources.
VRE penetration threshold	Low penetration level. Diversification strategy is generally desirable starting from the first VRE generators.

Flexible thermal generation

Flexible thermal generation capacities can be installed in the system to address the operational challenges related to VRE output variability. This can either be in addition to or as replacement to existing thermal capacities. Replacement of old diesel generators by more modern ones[44] with lower start-up times, higher ramping capabilities, faster governor response and better efficiencies at part load can, for example, be considered for SIDS. This generally allows more headroom for providing operating reserves.

This solution is particularly relevant in islands with old inflexible diesel generators that are targeting medium VRE penetration levels. The installation of new flexible thermal generation in a system can help to mitigate adequacy, intraday flexibility and stability issues.

However, this solution can no longer be applied when 100 % VRE penetration is targeted (on an annual energy basis), since these generators run on fuels[45].

Table 22 presents further details on flexible thermal generation as a solution for VRE integration and its applicability to SIDS.

Energy storage

Generally, electricity storage can be used to store VRE production under unfavourable technical or economic conditions and to dispatch it later in more favourable periods. Because storage can absorb VRE output at times when it could pose operational challenges to the system, it can help mitigate most of these challenges.

At a system-wide level, storage assets can be used over different time frames, depending on the characteristics of the chosen technology:

- ***Within seconds***: some storage technologies (*e. g.,* flywheels) can directly provide rotational inertia to the system, while others (*e. g.,* batteries) can mimic inertia and provide primary reserves through very fast automated response to frequency changes.
- ***Within minutes***: storage assets can provide secondary frequency reserves and help compensate for the ramping of VRE generators.
- ***Within 10 minutes – hours:*** storage can be used and optimised as part of the generation scheduling process in order to perform time-shifting of load/generation.

Table 22: Solution summary – flexible thermal generation

VRE integration challenges addressed	Significant impact: adequacy (if capacity addition), intraday flexibility, stability.
Integration in technical studies	Influences the capacities and characteristics of thermal generators considered in all studies.
Relation and synergies with other solutions	Synergistic with automatic power controller, and adapted generation dispatch and control. Competing with all other solutions providing flexibility.
Applicability to SIDS	Low-to-medium applicability. In small islands installed thermal generation is generally made up of diesel generators that are more flexible than larger-scale technologies (*e. g.*, coal-fired power plants or combined-cycle gas turbines).
VRE penetration threshold	Medium penetration level. Transition solution not applicable for 100 % VRE penetration (year-round).

44 Solutions under discussion also include small diesel generators and low loading generators.

45 However, running the generators with biofuels would allow for targeting 100 % renewable energy penetration on an annual energy basis.

While storage is generally used for such system-wide applications related to load-generation balancing, it also can help mitigate grid-related issues in transmission and distribution networks. This includes, for example, relieving congestions or voltage issues on some parts of the grid and improving power quality (with fast-acting storage technologies).

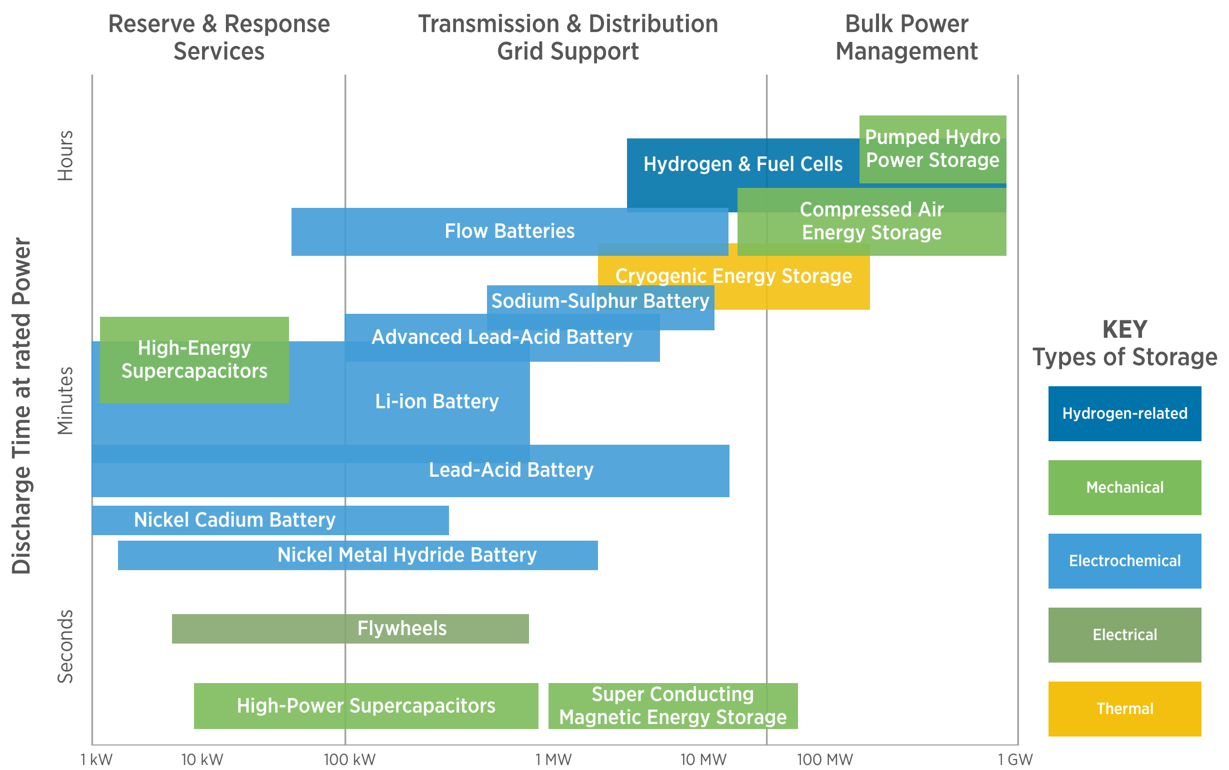
Figure 36 provides an overview of the main technical characteristics of the different storage technologies, *i. e.,* the power rating per module and the discharge time at rated power. These characteristics influence the range of practical applications for which each technology is suitable, and in particular the time frames at which it can be used. For example, the technologies with low discharge times (from seconds to minutes) cannot really help in solving the issues of sustained VRE unavailability (*e. g.,* periods of consecutive cloudy days for solar PV generation).

Battery technologies are mature and are the most popular storage solution due to the cost declines observed in recent years as well as their general applicability, being virtually independent of topological conditions. Small-island power systems are particularly suitable for battery storage systems due to the lower system size compared to larger interconnected systems.

Other technologies such as flywheels, supercapacitors or hydrogen-based storage are also used commercially in some systems, but with limited global uptake by utilities due to their high capital and operational costs.

Real-life examples of storage applications to facilitate VRE integration in islands are discussed in Box 7.

Figure 36: Main characteristics and applications of storage technologies



Source: Taylor *et al.,* 2012.

BOX 7: EXAMPLES OF REAL-LIFE STORAGE USE IN ISLANDS TO FACILITATE VRE INTEGRATION

Graciosa, the second smallest island in the Azores, is equipped with a megawatt-scale lithium-ion (Li-ion) battery storage system (4 MW/3.2 MWh). This grid-forming storage system allows for an instantaneous renewable share of 100 %, coming from a 4.5 MW wind park and a 1 MW solar PV power plant. As a result, approximately two-thirds of the island's electric energy requirements are supplied by renewable energy.

Due to the remoteness of the island, the savings in diesel fuel outweigh the investments, thereby delivering electricity at a lower cost. The battery system provides ancillary grid services such as voltage and frequency control, and it is also used to optimise the dispatch of the energy coming from the renewable sources. Without such grid-supportive capabilities, a 100 % renewable share would be impossible, as conventional generators would be activated and running at their minimum output for the sole purpose of providing grid stability (Younicos, 2017a).

Photograph:Younicos/Aggreko (all rights reserved).

Photograph:Younicos/Aggreko (all rights reserved).

Lanai is a US Hawaiian island that has more than 270 sunny days per year, making it an extremely suitable location for solar energy. A 1.2 MW solar PV plant has been constructed, feeding the island's grid with a 4 MW peak load. However, the intermittency of the PV power output poses challenges to grid stability, leading to forced curtailment of up to 50 % of the PV plant's output. Furthermore, the PV plant is required to provide frequency response to the grid, leading to further reductions in energy production.

A battery storage system with a rated power of 1.125 MW for a duration of 15 minutes was added to the PV plant, providing ramp control, frequency response and power quality management. Thanks to this battery storage system, the PV plant's power output does not have to be curtailed (Younicos, 2017b)

Photograph:Younicos/Aggreko (all rights reserved).

Japan's Oki islands are equipped with a hybrid storage battery system, composed of sodium sulphur (NaS) and Li-ion batteries. The NaS battery (4.2 MW/25.2 MWh) stabilises large, slow fluctuations, while the Li-ion battery (2.0 MW/0.7 MWh) absorbs rapid, small fluctuations due to passing clouds or sudden changes in wind speed.

Through the operation of the hybrid storage battery system, the Chugoku Electric Power Company expects to introduce renewable energy capacity of over 10 MW, the minimum demand of the Oki Islands, by adding approximately 8 MW of new installations to the existing 3 MW, in the entire Oki archipelago (NGK, n.d.)

NGK INSULATORS, LTD. www.ngk-insulators.com/en/index.html

Table 23: Solution summary – electricity storage

VRE integration challenges addressed	Moderate to significant impact (depending on technology): generation adequacy, intraday flexibility, stability, static thermal/ voltage grid limits, power quality. Moderate impact: short-circuits and protections.
Integration in technical studies	Storage impact can be integrated in all technical studies. Particular modelling requirements include, for example: • the need to use chronological models for generation adequacy studies • the need to define storage active power injection/absorption scenarios for static network studies and regulation/control capabilities for dynamic network studies.
Relation and synergies with other solutions	Synergistic with adapted generation dispatch and control, demand response, distribution automation and accurate VRE forecast. Competing with all other solutions providing flexibility.
Applicability to SIDS	Medium-to-high applicability with battery technologies. Low applicability for pumped storage except in larger systems (>200 MW) with favourable topological sites*.
VRE penetration threshold	Medium penetration level. Not needed at low penetration.

* A notable exception to this is the small-scale pumped storage facility used in the island of El Hierro (part of the Spanish Canary Islands). This facility comprises hydro turbines for a total of 11.3 MW and pumps for a total of 6 MW. It allows for storing possible surplus energy from a 11.5 MW wind farm to which it is coupled. It also is used for irrigation purposes. The project benefited from the presence of a volcanic crater for its upper reservoir. However, it is unclear whether the project is economically viable, given its high investment cost (estimated at EUR 82 million for the entire wind-storage hybrid plant).

Table 23 presents further details on the implementation of electricity storage as a solution for VRE integration and its applicability to SIDS.

Conventional transmission and distribution grid reinforcements

In addition to the grid expansion investments that might be needed to connect remote VRE sites to the main system, reinforcements can be needed on existing portions of the transmission or distribution networks to accommodate VRE generators.

Conventional transmission and distribution grid reinforcements are assumed here to include:

- Installation of new overhead lines, underground cables and transformers, either in addition to the existing grid or as replacement of some equipment (with higher sizing).
- Passive reactive power compensation means such as fixed or mechanically switched capacitor or reactor banks. More advanced reactive power compensation means such as flexible alternating current transmission systems (FACTS) are discussed further as part of smart transmission grids and distribution automation solutions.
- Replacement of existing circuit breakers by equipment with higher short-circuit current capabilities.

Notably, some of these network devices also can have a positive impact on generation dispatch in view of integrating VRE. For example, reactive power compensation means have been used in some islands to avoid having to keep thermal generators online for voltage control purposes.

Table 24 presents further details on conventional transmission and distribution grid reinforcements as a solution for VRE integration and its applicability to SIDS.

Table 24: Solution summary – conventional transmission and distribution grid reinforcements

VRE integration challenge addressed	Moderate to significant impact (depending on technology): stability (rotor angle and voltage stability), static thermal/ voltage grid limits, short-circuit current and protection, power quality.
Integration in technical studies	Weak portions of the grid in presence of VRE will be highlighted by static, dynamic and special network studies. Candidate grid reinforcements can easily be integrated in the network models of these studies.
Relation and synergies with other solutions	Several other solutions (including storage or technical requirements on VRE generators) allow for reducing needed grid reinforcements.
Applicability to SIDS	Medium-to-high applicability. For new overhead lines and transformers at transmission level, land availability can be a challenge in small or touristic islands.
VRE penetration threshold	Low penetration level. Often among the least-expensive options at low VRE penetrations.

Interconnection with neighbouring systems

The applicability of interconnections is restricted to a few island grids where the geographical conditions allow interconnection to other island grids. Interconnecting a given power system with a neighbouring system having different load and generation characteristics can bring significant benefits due to the pooling of generation capacities[46].

In the context of VRE integration, interconnectors can help mitigate the challenges related to VRE variability, such as adequacy, ramping and stability challenges, either through planned energy exchanges or through a sharing of operating reserves[47].

The main limitation of this option is the required cost when high-depth seas and long distances have to be covered to reach neighbouring systems. Alternating current or direct current technologies can be used

Table 25: Solution summary – interconnection with neighbouring systems

VRE integration challenges addressed	Significant impact: generation adequacy, intraday flexibility, stability (frequency stability).
Integration in technical studies	Behaviour of the neighbouring system must be represented in all studies, except distribution network studies and grid connection studies. While representing both systems in full details (load, generation and grid) provides the most accurate results, simplified representation of the neighbouring system (*e. g.*, with an equivalent circuit) can already provide satisfactory results. Note: planning the interconnection requires detailed studies on its own that are not necessarily linked to VRE integration challenges (import/export flows might, for example, lead to congestions or voltage issues that have to be addressed).
Relation and synergies with other solutions	Operational co-ordination between system operators from the interconnected systems is required. Competing with all other solutions providing flexibility.
Applicability to SIDS	Low applicability. Not possible for very isolated islands. Can be used when distances and sea depths between islands are not too significant (*e. g.*, in archipelagos) or to connect different parts of a single island.
VRE penetration threshold	Medium penetration level. Not needed at low VRE penetration.

46 Note that the economic benefits are higher the more complementarity exists in the generation mix of the interconnected countries

47 Frequency is a system-wide phenomenon. Systems interconnected in alternating current share frequency control responsibilities (more generators can contribute); in addition, the inertia of the interconnected system is increased

for interconnectors, depending on the distance to be covered on land or under sea.

Table 25 presents further details on the interconnection with neighbouring systems as a solution for VRE integration and its applicability to SIDS.

Smart transmission grids

Three main types of smart transmission grid solutions can be considered in the context of large SIDS:

- ***FACTS,*** which use power transistors to control grid voltage and provide reactive power compensation, improving voltage stability and power quality. The most common FACTS technologies are static VAR compensators (SVCs) and static synchronous compensators (STATCOMs).

- ***Dynamic line rating*** (DLR) technology, which can measure and predict the instantaneous thermal rating of transmission lines based on parameters such as vibrations, temperature, sag, wind speed, etc. Integration of this information into grid operation practices allows for increasing the real-time maximum capacity of a line generally by at least 10%

- ***Synchrophasors***, or phasor measurement units (PMUs), which measure the magnitude and phase of transmission line current and voltage with high time resolutions (25 to 120 measures per second) (IRENA, 2013). Several PMUs can be used as part of a wide-area monitoring system (WAMS), leveraging their GPS-synchronised data to provide a precise and near real-time representation of the whole transmission system to grid operators. This allows for faster and more effective operational answers to prevent instabilities that could be caused by VRE. Such systems are relevant for large islands that could be faced with inter-area oscillations. They are presently used on the transmission system of Iceland, for example.

Table 26 presents further details on the implementation of smart transmission grids as a solution for VRE integration and its applicability to SIDS.

Table 26: Solution summary – smart transmission grids

VRE integration challenges addressed	Significant impact: stability, static thermal/ voltage grid limits. Moderate impact: power quality (for FACTS).
Integration in technical studies	FACTS and DLR can be integrated as part of the different static and dynamic network studies. Models for FACTS are commonly available within standard network power system simulation tools. Modelling the impact of DLR can be done by taking assumptions on the achievable increase of line thermal capacities. Impact of synchrophasors is rarely modelled as part of studies but rather assessed based on operational experience.
Relation and synergies with other solutions	DLR and synchrophasors require advanced energy management systems (EMS) to be implemented. FACTS and DLR can allow for avoiding some conventional transmission grid reinforcements. Synergies exist with accurate VRE forecast (for DLR and synchrophasors).
Applicability to SIDS	Low applicability. Sophisticated functionalities are only applicable in SIDS that have a transmission grid.
VRE penetration threshold	Medium-to-high penetration level. Only needed when large VRE power transfers are experienced on the island transmission grid.

Distribution automation

Distribution automation allows for increasing the controllability and observability of the distribution grid. It is relevant to solve grid challenges related to the integration of distributed VRE generation.

Two main types of distribution automation solutions can be considered in the context of SIDS:

- ***Volt/VAR control and optimisation:*** this includes a co-ordinated action of devices such as on-load tap changer transformers, voltage regulators and switched capacitor banks in response to real-time measurement of the voltage at different points of distribution feeders. Distributed FACTS are also starting to emerge in such schemes. Volt/VAR control can prevent voltage issues (*e. g.,* overvoltage) related to VRE integration. Control of distributed VRE generators can also be part of Volt/VAR control depending on the technical capabilities required from these generators (see section on technical requirements in this chapter).

- ***Automated fault location and restoration:*** this consists of adding sensing and intelligent control capabilities to breakers, switches, and reclosers. It allows for precisely locating faults on small sections of the distribution system and isolating the fault with automatic reconfiguration. It can be helpful to ensure proper functioning of the distribution protection schemes in the presence of reverse flows induced by distributed VRE generators (IRENA, 2013).

Table 27 presents further details on distribution automation as a solution for VRE integration and its applicability to SIDS.

9.2. Operational measures

This section discusses operational measures that can be implemented to solve VRE technical integration challenges.

Compared to infrastructure investments presented in the previous section, operational solutions generally require more limited investments for the utilities of SIDS and do not require installing large pieces of equipment.

Demand-response programmes

Demand response refers to the possibility, for system operators, of influencing the electricity consumption profile of grid users. Two main types of demand response can be distinguished, with different benefits for the integration of VRE:

- ***Dispatchable demand response***, which can be activated on short notice (within seconds or minutes) by system operators to reduce (or in some cases increase) the system demand in exchange for compensation payments. Direct load control schemes, interruptible contracts or other programmes to foster demand flexibility through operating reserves typically fall into this category. This can enable providing the necessary operating reserves for VRE integration without having to keep conventional generators online.

Table 27: Solution summary – distribution automation

VRE integration challenges addressed	Significant impact: stability (voltage), static thermal/ voltage grid limits, short circuits and protections.
Integration in technical studies	Volt/VAR control devices (such as on-load tap changers) can be integrated as part of static distribution grid studies.
Relation and synergies with other solutions	Usually require a distribution management system (DMS). Synergies with distributed storage and accurate VRE forecast.
Applicability to SIDS	Low-to-medium applicability. These functionalities are relatively sophisticated in the context of SIDS. Volt/VAR control can be useful if medium-high penetrations of distributed VRE are targeted.
VRE penetration threshold	Medium-to-high penetration level.

- ***Dynamic electricity tariffs***, which are based on an incentivised response from electricity users to changes in the electricity price (on time frames of several hours). Unlike with dispatchable demand response, there is no obligation for consumers to modify their consumption. Time-of-use, critical peak pricing and real-time pricing schemes fall into this category. These types of programmes are typically used to shift consumption from high-price (peak) periods to low-price (off-peak) periods. This kind of demand response cannot provide operating reserve but it can serve to shift consumption to times when VRE is the most available (and, for example, reduce potential VRE curtailments).

Historically these programmes were first developed for commercial and industrial consumers (due to their high consumption per site), but residential demand response is now also growing. In SIDS, the typical types of loads that could be interrupted or shifted within demand-response programmes include:

- air conditioning, cold storage and water heating loads, from commercial (*e. g.,* hotels) or residential customers;

- water pumping and desalination facilities of water utilities;

- charging of electric vehicles.

Some examples of demand response uses in islands are given below. Except for a few cases (such as Hawaii), existing uses are generally limited to small-scale or pilot programmes:

- ***King Island*** (Australia): The local utility (Hydro Tasmania) uses direct load control and promotes the use of electricity (through a web app/portal) when renewable energy from wind and solar resources is abundant. Direct load control amounts to 100 kilowatts (kW) (for a peak demand of 3 300 kW) and is applied to both commercial and residential customers (water heating and electric vehicles) (Hydro Tasmania, 2016).

- ***Hawaii islands*** (United States): a large range of direct load control programmes exist in Hawaii. Events can either be dispatched by local system operators or automatically triggered in case of underfrequency. "Dispatch events may last for at least one hour, and underfrequency events typically last for only a few minutes" (Hawaiian Electric Company, 2016). Ongoing programmes include:

    - Residential direct load control on water heaters (15 MW controllable from 34 000 customers) and air conditioning (2.5 MW controllable from 4 000 customers).

    - Direct load control for large commercial and industrial customers (18.2 MW from 43 customers) and for small businesses (1 MW from 161 customers) (Hawaiian Electric Company, 2016).

- ***Barbados***: Barbados Light & Power has a pilot programme offering time-of-use rates and interruptible service rates to commercial customers. Customers under interruptible service rates have to be able to reduce their load within 30 minutes (BLPC, 2015).

- ***La Réunion and Guadeloupe*** (France): Demand response has been applied to water heating and air conditioning loads in the framework of the Millener demonstration project of the utility EDF.

Table 28 presents further details on demand-response programmes as a solution for VRE integration and its applicability to SIDS.

Table 28: Solution summary – demand-response programmes

VRE integration challenges addressed	Significant impact: adequacy, intraday flexibility, stability (frequency). Moderate impact: static thermal/ voltage grid limits.
Integration in technical studies	Can be integrated as part of adequacy, generation scheduling and frequency stability studies. Simple load interruptions can easily be modelled since it has a similar behaviour to load shedding. Precise modelling of time-shifting behaviour requires more advanced models in adequacy and generation scheduling studies to represent the particular time-shifting characteristic behaviour of enrolled consumers (predictive aspect).
Relation and synergies with other solutions	Usually requires advanced metering infrastructures at customer's site as well as a demand-response aggregation platform for utilities. Synergies with accurate VRE forecast. Competing with all other solutions providing flexibility.
Applicability to SIDS	Medium applicability. Such programmes can leverage the fact that a significant number of customers are generally equipped with backup on-site diesel generators in SIDS, which could facilitate their participation in demand-response programmes.
VRE penetration threshold	Medium-to-high penetration level.

Adapted generation dispatch and control

Adapting generation dispatch and control strategies is generally one of the first options considered by utilities of SIDS to accommodate increasing levels of VRE in their system. This is because of the relatively low cost of such measures and the ease of implementation in the short term.

The following measures in particular can be taken:

- Include more synchronous generators (*e. g.,* diesel generators) in the dispatch at lower power output to provide sufficient operating reserve. This solution often can be implemented with an existing fleet of generators, without requiring new investments. However, it can lead to some increased generation costs and to some VRE curtailment.

- Remove must-run constraints on some generators that have to be kept online for voltage control purposes (*e. g.,* in combination with network reactive compensation equipment).

- Use VRE curtailment at periods of low demand and high VRE generation.

- Implement automatic generation control on the different generators above a certain size (*e. g.,* 1 MW) in order to easily modify their power output set-points (when it is not yet implemented).

- Adapt the settings of the governors (*e. g.,* droop) to improve the primary frequency response from generators.

- Introduce operational planning procedures to optimise generation scheduling in hours or day-ahead based on latest available information (including VRE forecast).

- Define new types of operating reserves, adapted to the variability characteristics of VRE, in addition to the single spinning reserve requirement generally applied in SIDS. Separating primary and secondary reserve needs (at different time frames) and using downward operating reserves (*i. e.,* generation reduction or load increase) in addition to the existing upward reserves can also be contemplated.

Most of the above-listed measures that are related to generation dispatch can be implemented within the energy management systems (EMSs) of power utilities. Some EMSs can, for example, automatically dispatch thermal machines to provide the required operating reserve and minimise fuel consumption while taking into account the operational constraints on generators

Table 29: Solution summary – adapted generation dispatch and control

VRE integration challenges addressed	Significant impact: intraday flexibility, stability (frequency). Moderate impact: adequacy, static thermal/ voltage grid limits.
Integration in technical studies	The different measures can generally be integrated as part of the different studies in a relatively straightforward way by adapting model inputs related to generators operation and control (dispatch, governor parameters, voltage set=points, etc.)
Relation and synergies with other solutions	Synergies with accurate VRE forecast, conventional transmission and distribution grid reinforcements, smart transmission grids and automatic power controller and network monitoring. Competing with other solutions providing flexibility.
Applicability to SIDS	High applicability due to relatively low cost and ease of implementation.
VRE penetration threshold	Low-to-medium penetration level.

(*e. g.,* technical minimum). These generation-related functionalities of EMSs complement the network-related functionalities described further in this guide.

Table 29 presents further details on adapted generation dispatch and control as a solution for VRE integration and its applicability to SIDS.

Adapted defence plans

Reviewing the defence plans that are currently in use is another effective way to solve some VRE integration challenges. This can, for example, include a revision of the following schemes to allow for stable operation of the system in the presence of VRE:

- under-frequency load shedding (UFLS)
- over-/under-voltage load shedding (OVLS/UVLS)
- automatic connection/disconnection of reactive power compensation equipment
- instructions for transformer tapping
- out-of-step protection.

For more information on these solutions, see the description of dedicated defence plan studies in Chapter 8 of this guide.

Table 30: Solution summary – adapted defence plans

VRE integration challenges addressed	Significant impact: stability (all types), static thermal/ voltage grid limits.
Integration in technical studies	See Section 8.1.
Relation and synergies with other solutions	Synergies with conventional transmission and distribution grid reinforcements, smart transmission grids, distribution automation, adapted generation dispatch and control and automatic power controller and network monitoring.
Applicability to SIDS	High applicability due to relatively low cost and ease of implementation.
VRE penetration threshold	Low-to-medium penetration level.

Table 30 presents further details on adapted defence plans as a solution for VRE integration and its applicability to small-island.

Automatic power controller and network monitoring

A small-island power system, in its transition to provide cleaner and reliable power with higher levels of VRE penetration, requires a high-level control that is capable of monitoring and operating the various generation and enabling technologies.

This type of control supports the determination, in real time, of the required level of spinning reserve and the power set-points for all generating elements. It can achieve improved flexibility through its ability to optimally schedule active and reactive power reserves and to participate in demand-side management and VRE curtailment solutions. A high-level control makes it possible to minimise the use of conventional power sources and makes the power system more resilient and flexible in nature.

Most utilities in SIDS are equipped with basic network monitoring tools that use legacy supervisory control and data acquisition (SCADA) technologies. Updating these with modern EMS or DMS tools with advanced communication, control and optimisation capabilities can facilitate the operational management of the system in the presence of VRE.

Case studies that involve application of the EMS system include the Lanai battery park (see Box 7) and the King island advanced hybrid power station (see Box 8).

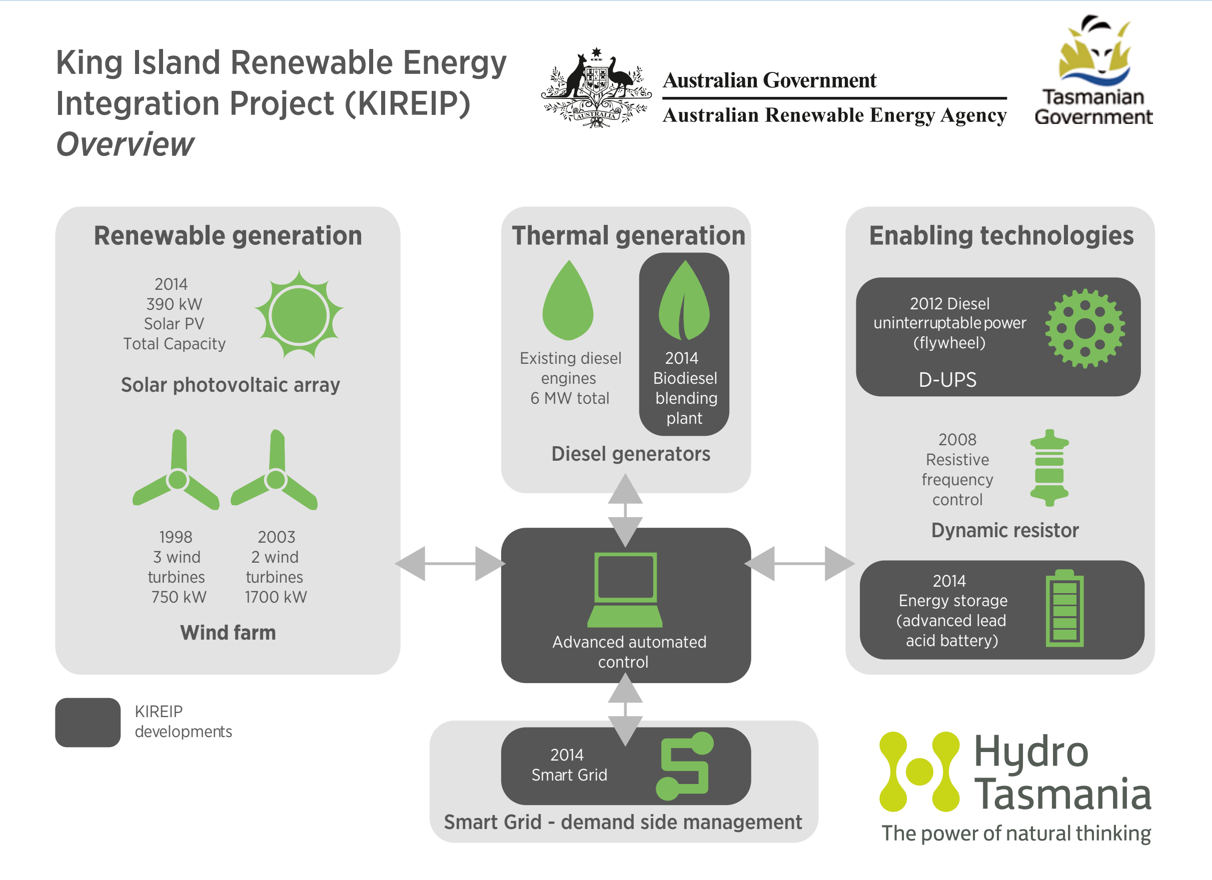
Table 31 presents further details on automatic power controller and network monitoring as a solution for VRE integration and its applicability to SIDS.

Table 31: Solution summary – automatic power controller and network monitoring

VRE integration challenges addressed	Significant impact: stability (all types), static thermal/ voltage grid limits.
Integration in technical studies	Not applicable (enabler for other solutions).
Relation and synergies with other solutions	Synergies with most other solutions.
Applicability to SIDS	Medium applicability. SIDS' systems generally have lower complexity, requiring less sophisticated monitoring and control than larger systems.
VRE penetration threshold	Medium penetration level.

BOX 8: COMPREHENSIVE HYBRID SYSTEM FOR VRE INTEGRATION IN KING ISLAND (AUSTRALIA)

The Advanced Hybrid Power Station installed in King Island, Australia, groups, at a single location, several VRE installations (solar PV and wind) as well as the solutions to avoid any technical issue with their integration. These solutions include: diesel engines, two different storage systems (battery and flywheel) and a dynamic resistor (used as a dump load in case of VRE surplus, and contributing to frequency regulation). It also can interact with customers on the island to activate demand-response capacities. The aim of the project is to enable attainment of a 65 % renewable energy share (annually) and up to 100 % instantaneous penetration when VRE sources are abundant. The four 11 kV distribution feeders of the island are directly supplied by this hybrid plant.



The main challenge of this kind of project lies in the sizing and design of the different equipment of the hybrid plant as well as in the choice of an optimal control scheme for its operation.

Source: Hydro Tasmania, 2016.

Accurate VRE forecasts

Accurate forecasting of VRE power output (especially wind and solar) can help to mitigate the operational challenges related to its uncertainty. In particular, accurate forecasts are important when performing generation scheduling at the operational planning stage (*e. g.,* in day or hours ahead). Forecast errors can lead to inefficient dispatch of the different generators in the system and to more frequent activation of operating reserves. Forecasting tools are currently more mature for wind than for solar generation (when considering variations due to cloud cover or other shading).

Table 32 presents further details on the use of accurate VRE forecasts as a solution for VRE integration and its applicability to SIDS.

9.3. Technical requirements for variable renewable energy generators

Imposing technical requirements on VRE generators is an effective way to prevent undesirable effects on the power system. Many different requirements can be imposed ranging from very simple ones needed at low VRE penetrations to very advanced ones needed to reach near 100 % penetration. Table 33 presents a summary of the technical requirements for VRE generators as a solution for VRE integration and its applicability to SIDS.

For detailed information on possible technical requirements that can be imposed on VRE generators, see IRENA (2016a). Two main synthesis tables from this report are reproduced in Tables 34 and 35:

- Table 34 shows the approximate penetration levels at which the different requirements become applicable. All listed requirements remain necessary when the next VRE penetration level is reached.
- Table 35 shows the ease of implementation of different technical requirements for the main types of VRE (and interfaces with the grid).

Almost all technical challenges related to VRE integration can be addressed (at least in part) by imposing technical requirements on VRE generators. The most notable exception to this is the adequacy challenge in the case of sustained unavailability of VRE over several hours or days.

In systems where several stakeholders can operate VRE (*e. g.,* IPPs, residential customers with distributed solar PV, etc.), these requirements can be imposed by a grid code. For systems where an integrated utility operates most VRE, which is often the case for SIDS, integration of these requirements in internal VRE procurement and operational procedures can be sufficient. Box 9 provides an example of the technical requirements that have been adopted in Hawaii for increased penetration of renewables.

Table 32: Solution summary – accurate VRE forecasts

VRE integration challenges addressed	Significant impact: stability (all types), static thermal/ voltage grid limits.
Integration in technical studies	Forecast errors can be considered for operating reserve sizing and within generation scheduling studies (*e. g.*, to assess how they impact operational costs).
Relation and synergies with other solutions	Usually available as module within EMS or DMS tools. Dependent on availability of reliable weather forecast service. Synergies with storage, demand response, distribution automation, smart transmission grid, adapted generation dispatch and control.
Applicability to SIDS	Medium applicability. Weather forecast in small islands is less accurate than over larger areas.
VRE penetration threshold	Medium penetration level. Not economic at low penetrations.

Table 33: Solution summary – technical requirements for VRE generators

VRE integration challenges addressed	Moderate to significant impact (depending on technology): intraday flexibility, stability, static thermal/ voltage grid limits, short-circuits and protections, power quality.
Integration in technical studies	Partial controllability (*e. g.*, through curtailment) of VRE active power and participation to operating reserves can be modelled as part of generation scheduling studies. VRE controllability and contribution to voltage/reactive control can be integrated within static grid studies. Detailed dynamic requirements on VRE generators capabilities (such as low-voltage ride through) can be integrated in stability studies. Power quality requirements for VRE can be integrated in the power quality part of grid connection studies.
Relation and synergies with other solutions	Synergies with distribution automation, adapted generation dispatch and control, and automatic power controller and network monitoring.
Applicability to SIDS	Medium-to-high applicability. Because SIDS power systems are generally small and managed by vertically integrated utilities, fewer stakeholders are involved and changes in requirements for VRE generators can be easier to apply than in more complex market-based environments.
VRE penetration threshold	Low-to-high, depending on the requirement (see Table 34).

Table 34: Applicability of different technical requirements for VRE at increasing penetration levels

Always needed	• protection • power quality • power reduction during over-frequency
Low VRE penetration	• communication • adjustable reactive power • constraining active power (active power management)
Medium VRE penetration	• LVRT including current contribution • simulation models
High VRE penetration	• active power gradient limitation • reduced output operation mode for reserve provision • synthetic inertia
Exclusive use of VRE	• stand-alone frequency control • full integration into general frequency control scheme • stand-alone voltage control • full integration into general voltage control scheme

Based on IRENA, 2016.

Table 35: Ease of implementing grid code requirements for different VRE technologies

Requirement	Synchronous machine	PV converter	Wind turbine with full converter	Wind turbine with DFIG	Wind turbine with SCIG
Power quality: harmonics	No issues	Depends on design, and needs integrated filters	Depends on design, and needs integrated filters	Depends on design, and needs integrated filters	No issues
Power quality: flicker	No issues	No issues	Mitigation via control	Mitigation via control	Poor power quality
Reactive power capability	Wide capability range	Converter can provide wide range of reactive power if sufficiently dimensioned	Converter can provide wide range of reactive power if sufficiently dimensioned	Limited capability, controlled by rotor side converter; may require extra equipment	reactive power not controllable, needs additional compensation equipment
Frequency support: generation reduction at over-frequency	Full control	Full control, maximum is subject to irradiation	Full control, maximum is subject to wind conditions	Full control, maximum is subject to wind conditions	Limited controllability via pitch and/or rotor resistor
LVRT, including current contribution	Can be achieved within converter, which can supply current during fault	Can be achieved within converter, which can supply current during fault	Can be achieved within converter, which can supply current during fault	Can be achieved within generator and converter control	Requires significant additional equipment
Inertia	No issues	Complex implementation of synthetic inertia, may require storage	Complex implementation of synthetic inertia	Complex implementation of synthetic inertia	No issues

Based on IRENA, 2016.

9.4. Selection of solutions

Given the large choice of possible solutions to address VRE grid integration challenges, selecting the most appropriate ones for a given SIDS can be a challenge.

A recommended approach is to perform an initial qualitative screening of possibly suitable solutions by mapping the identified technical challenges at the targeted VRE penetration level with the ability of the different options to solve these challenges. Other factors that can be considered are the practical and logistical applicability of solutions in a given context, their commercial availability, the required capital investments, the timeline for implementation, environmental impacts, etc.[48]

Table 36 provides a summary of the information provided in previous sections that can help when conducting the initial screening to select a few candidate solutions.

Once candidate solutions have been chosen, they should be assessed by means of technical studies to ensure that they will indeed solve the identified violations of performance criteria with targeted VRE shares.

48 These factors have been aggregated in the indicator "applicability to SIDS" used throughout this chapter

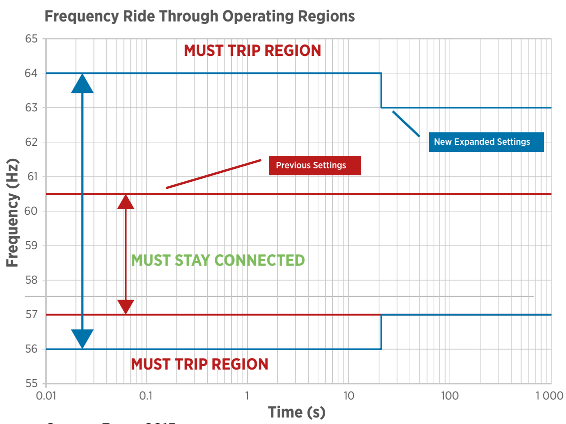
BOX 9: HOW TECHNICAL REQUIREMENTS FOR VRE GENERATORS HELPED INCREASE VRE PENETRATION IN HAWAII

A popular example of grid code adaptations that have been implemented in connection with growing VRE penetration in islands is the case of Hawaii. In 2014, the large amount of solar PV capacity installed on the grid led to two frequency-related events on Oahu Island. About 600 MW of VRE (including 220 MW of solar PV) was present at that time, for a peak load close to 1 200 MW.

Through modelling and simulations, new grid code requirements were computed to make the system more robust to voltage/frequency stability issues. These requirements were imposed on PV inverters at the end of 2014. They related mainly to new "advanced settings" with regard to transient overvoltage and voltage/frequency ride-through parameters (see figures below). Software upgrades were implemented remotely by inverter manufacturers in order to comply with the new rules.

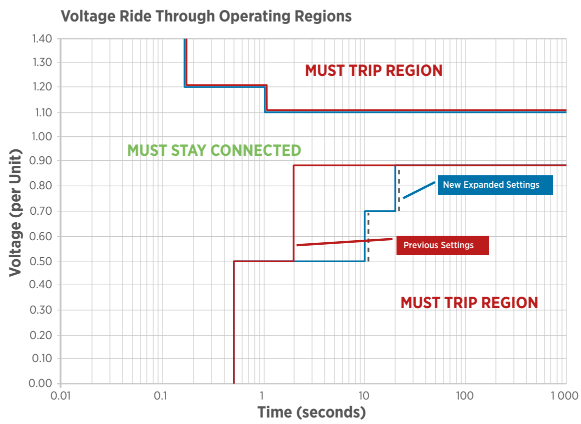
This enabled a decline in the growing backlog of applications for new solar installations on the island.

Low/High Frequency Ride-Through



Source: Fong, 2015.

Low/High Voltage Ride-Through



When multiple solutions can address the same technical challenges, the final selection should be based on a cost-benefit analysis. Such analysis can be conducted on each individual solution but also on hybrid mixes of solutions. Detailed guidelines on how to perform such cost-benefit analyses in the context of developing countries are available in IRENA (2015b).

Box 10 provides an example of the selection of technical solutions to increase VRE penetration in Samoa. The set of solutions obtained during this process is valuable input to the cost-benefit analysis, where the decision is made regarding implementation of the optimum set of mitigation measures.

Most solutions allow for other benefits than simply enabling VRE integration. For example, distribution automation can also help to reduce losses and increase reliability in distribution grids. The cost-benefit analyses should ideally consider these additional benefits when comparing different solutions.

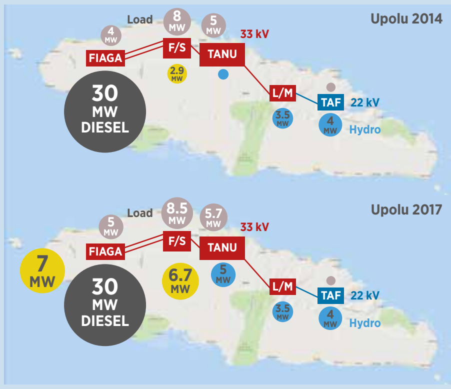
Table 36: Mapping of technical solutions with addressed challenges and other evaluation criteria

		VRE integration challenge addressed						Other evaluation criteria	
	Solutions	**Generation adequacy**	**Intraday flexibility**	**Stability**	**Static thermal/ voltage grid limits**	**Short circuits and protections**	**Power quality**	**Applicability to SIDS**	**VRE penetration threshold**
Infrastructure investments	Diversification of VRE installations	High impact	High impact	High impact	High impact	Moderate impact	Moderate impact	Low – medium	Low
Infrastructure investments	Flexible thermal generation	High impact	High impact	High impact	(Almost) no impact	(Almost) no impact	(Almost) no impact	Low – medium	Medium
Infrastructure investments	Electricity storage	High impact	High impact	High impact	Moderate impact	Moderate impact	High impact	Medium – high	Medium
Infrastructure investments	Conventional transmission and distribution grid reinforcements	(Almost) no impact	(Almost) no impact	High impact	High impact	High impact	High impact	Medium – high	Low
Infrastructure investments	Interconnection with neighbouring system	High impact	High impact	High impact	(Almost) no impact	(Almost) no impact	(Almost) no impact	Low – medium	Medium
Infrastructure investments	Smart transmission	(Almost) no impact	(Almost) no impact	(Almost) no impact	High impact	High impact	Moderate impact	Low	Medium – high
Infrastructure investments	Distribution automation	(Almost) no impact	(Almost) no impact	(Almost) no impact	High impact	High impact	High impact	Low – medium	Medium – high

Legend | **High impact** | **Moderate impact** | **(Almost) no impact**

BOX 10: SOLUTIONS TO INCREASE VRE PENETRATION – UPOLU CASE STUDY (SAMOA)

In 2014 the government of Samoa started an ambitious plan to integrate high amounts of renewable energy generation into its power system. By request of the government, in 2015 IRENA engaged with the power utility EPC in a study to assess the impact of the planned solar PV and wind power generation projects on reliable and stable operation and to identify appropriate measures to solve the potential technical problems. The study focused on Samoa's main island of Upolu, home to around 75% of the country's population.



Map source: Google, 2017; Data source: IRENA, 2015d, unpublished.
Boundaries shown do not imply any official endorsement or acceptance by IRENA.

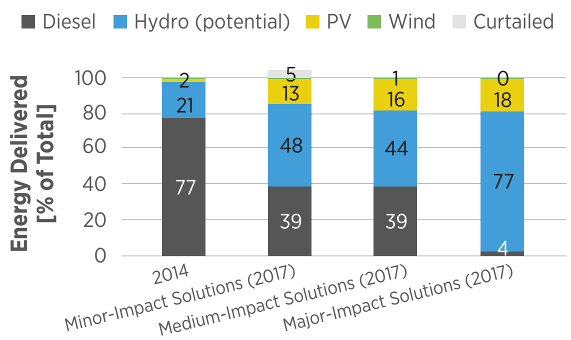
By 2014 the power system in Upolu had an installed capacity of 29.8 MW of diesel generation, 8.5 MW of hydropower, 2.85 MW of solar PV and 0.55 MW of wind power. The annual electricity demand was around 115 GWh, with a peak demand occurring at noon of 20 MW.

The utility's expansion plan for 2014–2017 was used as the base case for the study. The plan included the addition of 11 MW of new solar PV, 1.8 MW of new hydropower as well as the rehabilitation of 3.4 MW of existing hydropower plants.

The conducted analyses followed the procedures described in this guide. Generation adequacy assessments as well as steady-state and dynamic network studies at transmission level were done.

Iteration	Solutions applied	Limitation Criteria
# 2 (Minor-Impact Solutions)	• At least two diesel units online at all times – Voltage control capabilities in all PV plants with ± 0.95 power factor	Blackout after loss of generation or demand, or after fault
#3 (Mid-Impact Solutions)	• Solutions applied in Iteration 2 • Adjustment of UFLS settings • Output power reduction in case of overfrecuency for new PV plants – FRT capability for new PV plants	All criteria fulfilled
#4 (Major-Impact Solutions)	• Solutions applied in Iteration 3 • 3.5MVar reactive power compensation device • 4 MW/2 MWh Battery Energy Storage System • Automatic generation control includes hydro units	All criteria fulfilled

Source: IRENA, 2015d, unpublished.



Source: IRENA, 2015d, unpublished.

The results of the grid study for the base case showed that in 2017 the generation from the main diesel power station could be reduced considerably. However, the diesel generators could not be turned off, even if enough solar PV and hydro resources were available to cover the demand, due to the services that they provide for frequency and voltage control. In addition, the results showed that energy curtailments above 5% in VRE were expected for stability/security reasons. The study also identified Issues with voltage control in the areas where high concentration of solar PV was expected.

To overcome the identified issues, different infrastructure investments and operational measures were proposed as solutions, as shown in the table to the left. To identify appropriate solutions, simulations were run in an iterative process, incorporating solutions and analysing the fulfilment of previously defined operability criteria for the system.

As a result of this process a set of Mid-Impact and Major-Impact solutions (iterations 3 and 4 in table to left) fulfilled all of the criteria for the operation of the system.

The effectiveness of the measures proposed was then assessed in terms of the potential annual contribution of the PV and hydropower generation, assuming the full availability of hydro resources. As seen in the figure at bottom left, the contribution of renewable energy sources in 2017 had the potential to increase from 60% (for a Mid-Impact set of solutions) to 95% (for a Major-Impact set of solutions). Note that the actual shares will depend on the actual amount of available water resources.

This result represented a valuable input to the next phase, the cost-benefit analysis, where the decision was made regarding implementation of the optimum set of mitigation measures.

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GLOSSARY

Term	Description
Active power	The part of alternating current power that can perform work (reproduced or adapted from IRENA (2016a)).
Adequacy	"The ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements" (NERC, 2007). It applies to both the generation system and the electricity grid (transmission or distribution).
Critical clearing time (CCT)	Maximal fault duration for which the system remains transiently stable.
Curtailment	The reduction of the active power output of a variable renewable energy generator below the maximum it could produce in the prevailing conditions (wind, irradiation, temperature, rain, etc.). It is sometimes also referred to as spill over (reproduced or adapted from IRENA (2016a)).
Dispatchable generators	Generators that have a controllable and predictable power output such as conventional fossil-fuelled generators or controllable renewable generators (*e. g.*, biomass, geothermal and reservoir hydropower). They can be dispatched at the request of the operator.
Distribution system	The portion of the electric network dedicated to delivering electric energy to an end-user (EIA, n.d.).
Economic dispatch	Short-term process in which the power output of the different generators is decided in order to supply demand while minimising generation costs and complying with operational limits of the generating units and network assets. It often is performed in combination with the unit commitment process.
Electrical distance	The electrical distance relates to the total electrical impedance between two points in a power network. It reflects the opposition that the electrical circuit presents to an electrical current between these two points. This depends on the physical length of the circuit but also on the conductors' material and shape. The existence of parallel paths between two points reduces the electrical impedance/distance between them.
Energy management system (EMS)	Computerised control system that utilities use to monitor and operate various aspects of the generation, transmission and distribution of electricity.
Expansion planning	Power system expansion planning deals with mid- and long-term horizons, aiming at determining the least-cost strategy for long-range investments in expansion of generation, transmission and distribution systems in order to supply the forecasted demand while complying with a set of technical, economic and environmental constraints (IAEA, 1984).
Feeder	A distribution network power line that distributes electricity from a network substation to connected electricity consumers (reproduced or adapted from IRENA (2016a)).
Firm capacity	Amount of power generation that can be guaranteed to meet demand at any given time, even under adverse conditions (EIA, n.d.).

Flicker	Variations in voltage magnitude that would cause impression of unsteadiness of visual sensation.
Generation re-dispatch	Change of an initial generation dispatch strategy (typically defined by the generation scheduling process) in order to relieve technical constraints identified either during real-time operation or through close to real-time network studies (static and dynamic analyses).
Generation scheduling	Activity that consists in deciding, or optimising, the power outputs of the different generators of a power system for a certain time period in the future (*e. g.*, the day ahead). This encompasses the unit commitment and economic dispatch processes.
Grid code	Set of rules for power system and energy market operation. Grid codes enable network operators, generators, suppliers and consumers to function more effectively. This ensures operational stability and security of supply and contributes to well-functioning wholesale markets. Connection codes, operating codes, planning codes and market codes are a few examples of grid codes. Grid code rules for variable renewable energy generators typically specify the minimum technical and design requirements so that their behaviour is compatible with system stability and safety requirements (reproduced or adapted from IRENA (2016a)).
Harmonics	Oscillations in the voltage/current waves that occur at integer multiples of the system frequency. Harmonics add to the fundamental frequency, having as a result distorted, non-sinusoidal voltage/current waves that can affect the connected equipment (reproduced or adapted from IRENA (2016a)).
Hosting capacity	In the context of this work, power generation capacity (typically from variable renewable energy) that can be safely integrated in a given part of the power network without violating operational limits and without needing network reinforcements.
Inertial response	Intrinsic immediate response of synchronous machines (such as conventional generation units) to compensate imbalances between mechanical and electrical power.
Inverter	Power electronic device to convert direct current power, as in photovoltaic panels, to alternating current power as in a conventional grid (reproduced or adapted from IRENA (2016a)).
Low-voltage ride through	The ability of a generator to stay connected to the grid when the voltage falls below standard limits during a fault. Often used synonymously with fault ride through (FRT) (reproduced or adapted from IRENA (2016a)).
N-1 criterion	The rule according to which the power system must be able to sustain a list of normative single incidents, continuing operation without violations of the operational security limits.
Net load (or residual load)	Electricity demand minus the generation from variable renewable energy at a given time.

Normative incidents	Set of contingencies specifically foreseen in the planning and operation of the system, against which specific measures have been taken to ensure that no serious consequences would follow from their occurrence (ENTSO-E, 2010).
Operating reserves	Reserved active power capacity that can be called upon at different time frames in the case of a power deficit or surplus. Operating reserves can be broadly split into two categories: regulation reserves, used to compensate the continuous real-time variations of load and generation, and load-following reserves, used to compensate the error between the scheduled and the actual generation due to uncertainties on load and generation levels (reproduced or adapted from IRENA (2016a)).
Operational planning	Power system operational planning deals with the short-term horizon, assessing if the planned generation schedule can meet the forecasted load without resulting in violation of technical limits of the different power system equipment, as well as without endangering system stability and security. Available options to solve potential problems during operational planning time frame include the control variables of the generating units (active and reactive power), transformers (tap position), reactor and capacitor banks (taps) and network topology (network switching) as well as defence strategies such as load shedding.
Phase unbalance	Phase unbalance exists when the voltages on the different conductors of a three-phase system are not equal. This can lead to damages to electrical equipment (especially motors).
Power quality	Characteristic of a power supply for which the deviations in voltage, current or frequency signals are within acceptable ranges and do not result in failure or mis-operation of utility or end-user equipment.
Protection base time	Maximum intervention time (relay detection and circuit breaker opening) required for the protection system to operate.
Protection selectivity	Refers to the ability of the protection system to discern over-currents due to normal switching operation from fault currents.
Ramping	The change in active power output of a generator (or set of generators) over a defined period of time.
Reactive power	The part of the alternating current power responsible for building electromagnetic fields around components. Reactive power cannot perform work (reproduced or adapted from IRENA (2016a)).
Short-circuit current	Electrical current that flows through a circuit during an electrical short-circuit condition. A short circuit occurs when one or more electrical conductors of a power line contact ground and/or each other.
Stability	The ability of an electric system to maintain a state of equilibrium during normal and abnormal conditions or disturbances (NERC, 2007).
Stability margin	Expresses "how far" from instability a system is. In terms of transient stability, the stability margin can be quantified by the critical clearing time (CCT).

Synchronism	Synchronous machines operating in parallel at the same speed (measured in electrical radians per second).
Synchronous machine	An electrical machine whose rotating speed is proportional to the frequency of the alternating current supply and independent of the load. It is usually employed in conventional generating units to convert mechanical energy into electrical energy.
Synthetic inertia	Response of a non-synchronous generator having a power electronic interface with the grid, relating to the acceleration and deceleration of a power imbalance. The purpose is to imitate to some extent the inertial response of a synchronous generator (with a rotating mass) (reproduced or adapted from IRENA (2016a)).
Transient stability	The ability of the power system to maintain synchronism following a large disturbance. Synchronism can be defined as the ability of synchronous machines to operate in parallel at the same angle difference (with regard to a fixed angular reference) and at the same rotor speed (measured in electrical radians per second).
Transmission system	The portion of the system designed for long-distance electricity transmission over a network of interconnected group of lines and associated equipment (NERC, 2007).
Unit commitment	A process that consists in deciding, for each dispatchable generator, whether it will be producing power or not (on/off decision) at a certain time period in the future. The amount of power produced is determined by the economic dispatch process. The unit commitment takes into account technical constraints related to the flexibility of the generators, such as the time needed to start up.
Variable renewable energy	Energy from electricity generators such as wind turbines and solar panels that have a variable power output, which depends on the availability of the underlying primary renewable energy source (reproduced or adapted from IRENA (2016a)).
Variable renewable energy penetration	Different definitions of variable renewable energy (VRE) penetration can be found in the literature. The generic definition retained for this guide is the ratio between the total VRE power generation and the total power demand of a given power system (or a sub-part of it, such as a distribution feeder) at a certain point in time. This also is referred to as the instantaneous VRE penetration or instantaneous VRE share. VRE capacity penetration also is commonly used in literature and refers to the ratio between the installed VRE generation capacity and the annual peak demand on a power system.

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