IRENA
International Renewable Energy Agency

TRANSFORMING SMALL-ISLAND POWER SYSTEMS

TECHNICAL PLANNING STUDIES FOR THE INTEGRATION OF VARIABLE RENEWABLES

EXECUTIVE SUMMARY

Utilities in the small-island setting have to conduct thorough planning to integrate solar and wind power smoothly with existing grid infrastructure.

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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.

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?

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).

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[1] 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.

1 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 (see Figure 1).

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).

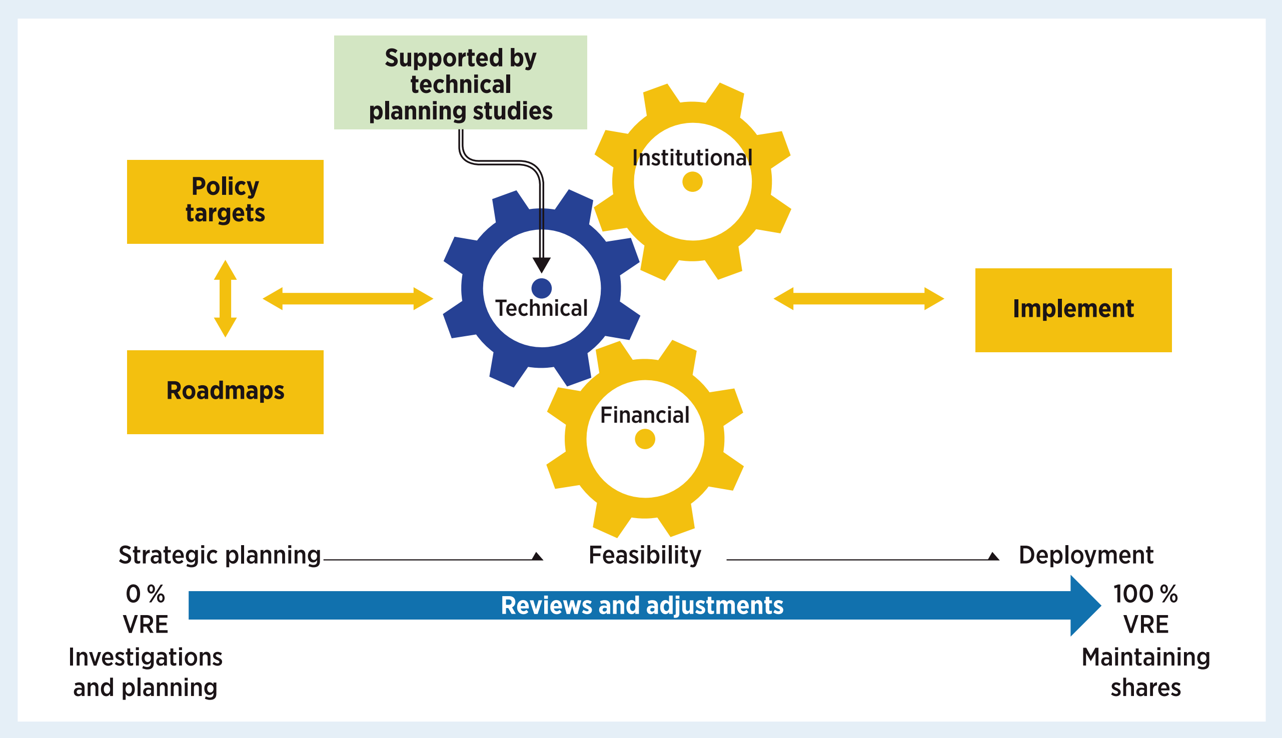
- **Demand and load profile.** The correlation between the system load and the expected VRE generation profiles is a key factor for VRE integration. This allows for determining the net load that needs to be supplied by the other non-VRE generators. Critical points are the level of the minimum load in 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.

- **VRE implementation strategy and generation expansion plans.** Will dispatchable (possibly thermal) generators be replaced with VRE? What is the future

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

Figure 1: The role of technical planning studies in the transformation of SIDS power systems



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 1: 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 1 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 2), as well as of the technical challenges addressed by each type of study (see Table 3).

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 2: 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 3: 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			Almost always applicable					
Sizing of operating re- serves				Applicable in specific situations	Almost always applicable			
Generation scheduling				Almost always applicable				
Network studies	Static	Load flow				Almost always applicable		
Network studies	Static	Static security assessment				Almost always applicable		
Network studies	Static	Short-circuit currents					Almost always applicable	
Network studies	Dynamic	System stability			Almost always applicable			
Network studies	Special	Grid connection			Almost always applicable	Almost always applicable	Almost always applicable	Almost always applicable
Network studies	Special	Defence plans			Almost always applicable	Almost always applicable		

Legend: 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).

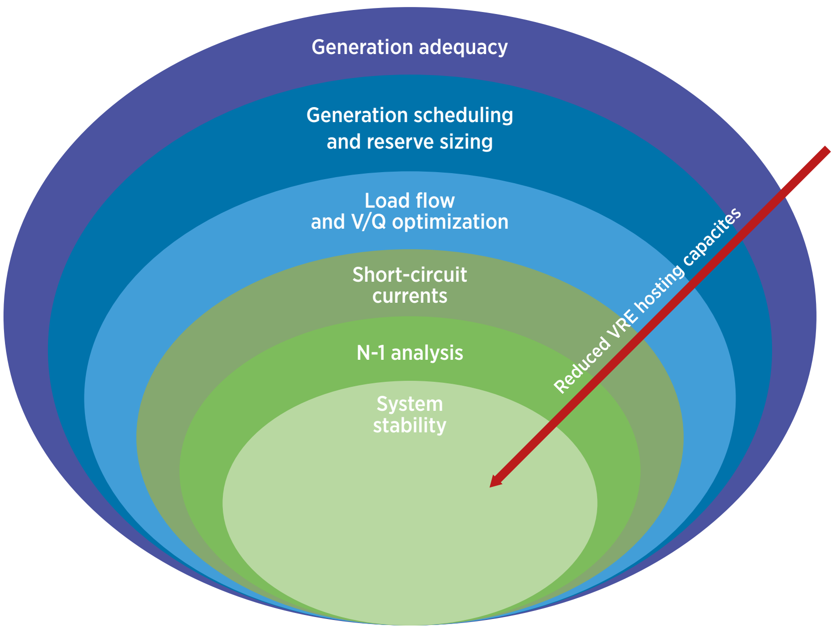
If at any point in time the share of **VRE generation stays below 10–15 %** of the total instantaneous load, the VRE penetration can be described as low and no significant integration issues are expected. However, this **does not mean that no study is required**, since dedicated grid connection studies 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 2 provides a general example of the different degrees of limitation to VRE integration posed by different studies[2] .

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

Figure 2: Limitations for VRE integration resulting from different technical studies



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 4). 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*. IRENA, Abu Dhabi. www.irena.org/publications/2013/Nov/Smart-Grids-and-Renewables-A-Guide-for-Effective-Deployment.

Table 4: 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

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