GRID CAPACITY GUIDELINE REPORT FOR THE INTEGRATION OF RENEWABLE GENERATION INTO THE GRID

Consultancy services to implement harmonised regulatory/technical frameworks and synthesised renewable and energy efficiency strategies in the EA-SA-IO region

Prepared for:

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This assignment will support the Common Market for Eastern and Southern Africa (COMESA), East African Community (EAC), Intergovernmental Authority on Development (IGAD), Indian Ocean Commission (IOC), and Southern African Development Community (SADC), in their collective efforts to promote the development of a sustainable regional energy market in the Eastern Africa, Southern Africa, and Indian Ocean (EA-SA-IO) region.

Guideline Report

This guideline report discusses the challenges related to increased integration of variable renewables in the region´s power grids, and outlines strategies for overcoming these. Based on these strategies it finally provides policy recommendations aimed at increasing the ability of regional grids to absorb low-cost renewables such as wind and solar.

Acknowledgements

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Opinions and Limitations

Unless otherwise indicated, the opinions herein are those of the authors and do not necessarily reflect the views of COMESA, EAC, ESREM, IGAD, IOC, or SADC.

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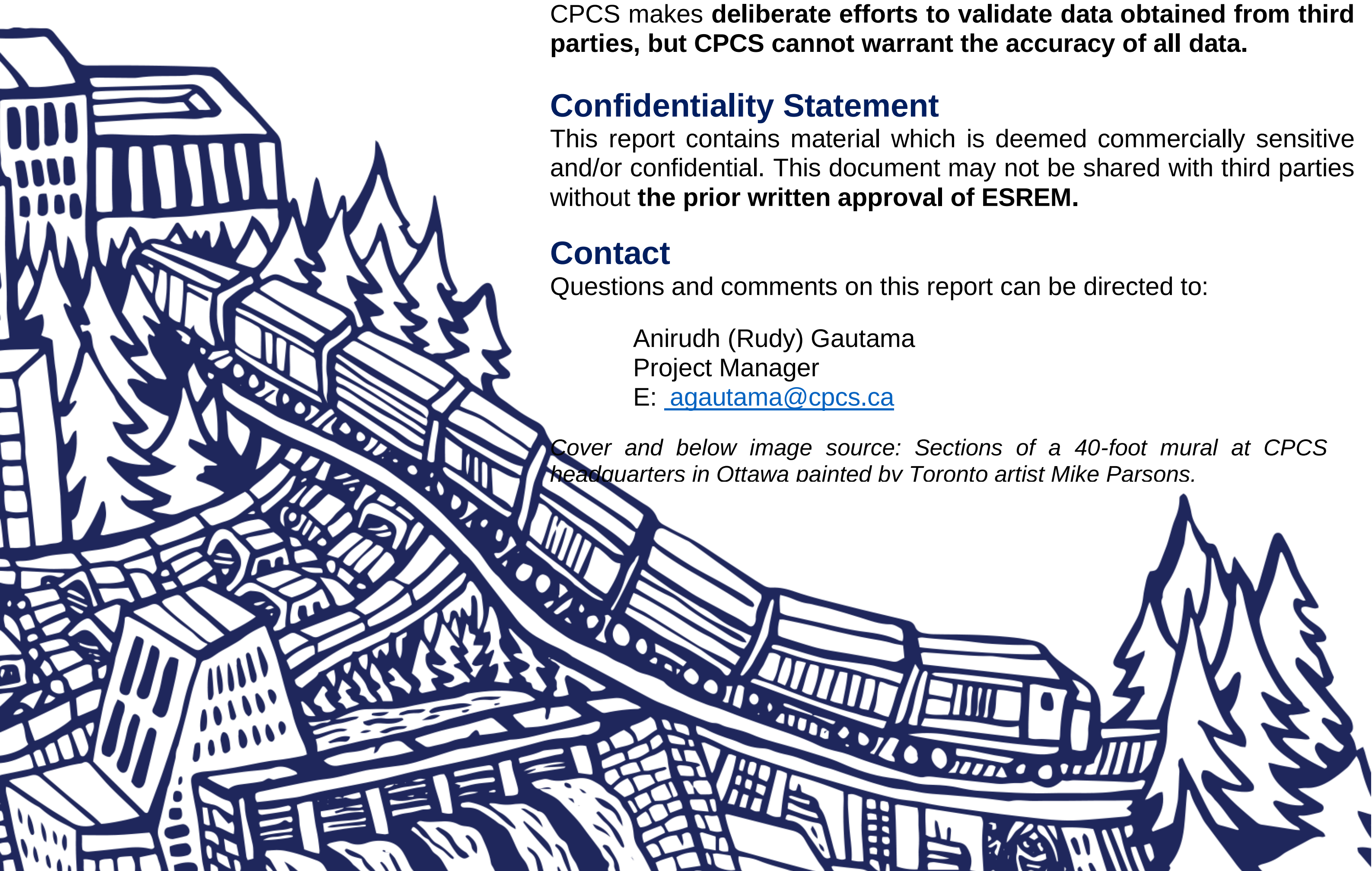

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Acronyms / Abbreviations

AC	Alternating Current
ACEC	African clean energy corridor
AfDB	African Development Bank
EAPP	Eastern African Power Pool
ESMAP	Energy Sector Management Assistance Program
ESREM	Enhancement of a Sustainable Regional Energy Market
GDP	Gross domestic product
GW	Gigawatt (one billion watts)
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IRENA	International Renewable Energy Agency
kV	Kilovolt (one thousand volts)
kW	Kilowatt (one thousand watts)
LV	Low-voltage
MV	Medium-voltage
MW	Megawatt (one million watts)
PV	Photovoltaic
RoCoF	Rate of Change of Frequency
SAPP	Southern African Power Pool
TWh	Terrawatthour (one trillion watts for one hour)
VRE	Variable Renewable Energy

Executive Summary

The Eastern Africa - Southern Africa - Indian Ocean (EA-SA-IO) region has considerable renewable energy resources, yet most countries in the region experience energy supply challenges manifested by inadequate levels and coverage of physical energy infrastructure. These challenges will continue to grow, because most countries in the region are expected to see increased demand from economic growth and population growth. As such, there is an urgent need to address energy poverty, manifested through low electricity access rates and a reliance on traditional fuels such as charcoal. In addition to energy poverty, energy supply challenges also drive up the cost of doing business, negatively impacting the competitiveness of the region in its internal and external markets.

Under the ongoing ESREM project, regional harmonised legal and regulatory frameworks and synthesised renewable energy and energy efficiency programs in the EA-SA-IO region are being drafted. The results of the project, once adopted, are expected to stimulate regional integration, energy trade and investment in energy markets across the region.

This Guideline Report addresses a core component of the project, namely to *review technical limitations in achieving a higher penetration of renewable energy and to propose related strategies for overcoming limitations* to assess *grid capacity*. This report provides the reader with an introduction to the attributes of different power generation sources and demand types as well as the technical limitations to transfer capacity in the components of the transmission grid and the physical phenomena that may constrain grid capacity from a technical perspective. The paper also aims to see this in the EA-SA-IO-regional context, by providing examples of typical capacity considerations relevant in selected representative example power systems. Sufficient grid capacity is key to unlock the full renewable energy potential in the region and to enable a green transition and the development of the power system in the EA-SA-IO region.

Grid capacity can be defined as the electricity grid's ability to receive, transport and supply power at all times. Numerous aspects and characteristics of the electricity grid impact the grid capacity. Grid capacity does not only refer to transfer capacity of the transmission and distribution grid, but also includes operational requirements on the supply (and demand) side.

Increased penetration of variable renewables makes power systems more complex, less predictable, and more distributed in nature. These impacts occur at all system levels, from local low-voltage through rooftop solar PV to large scale wind power plants connected to the high voltage transmission grid. As solar PV and wind power prices keep falling, VRE is likely to constitute a considerable share of the renewable energy mix in the region in the future. This means that flexibility and controllability measures will become increasingly important to ensure a safe and reliable electricity grid for the future.

The report presents analyses of the impacts and appropriate responses to increased shares of variable renewables in four generic power systems, representing four categories under which the countries in the EA-SA-IO region may be placed:

1. Island States

2. Fossil based, developed power systems

3. Partly renewable, intermediately developed power systems

4. Systems limited in size, consumption and renewables share Issues and measures to be considered do vary between the four categories. However, flexibility and proactive planning to ensure transfer capacity at all levels are important for all four. Therefore, the harmonised guidelines found in chapter five suggest that:

- New production should be subject to functional requirements instead of technical specifications
- Planning efforts should be coordinated – within the power sector and for all related sectors that use electric power
- Flexibility solutions should be enabled in all parts of the system
    - Interconnectors and key in-country transmission corridors can play an important role in unlocking the full renewable energy potential in the EA-SA-IO region and should be pursued
- Digitalisation and data driven power sector decisions should be pursued

1 Introduction

The Common Market for Eastern and Southern Africa (COMESA), East African Community (EAC), Intergovernmental Authority on Development (IGAD), Indian Ocean Commission (IOC), and Southern African Development Community (SADC) are jointly leading the implementation of a European Union-funded Project on the Enhancement of a Sustainable Regional Energy Market in the Eastern Africa, Southern Africa and Indian Ocean (EA-SA-IO) Region (ESREM).

The overall objective of the Project is to contribute to a sustainable regional energy market in the EA-SA-IO region[1], working towards a conducive investment environment and promoting sustainable development. As such, the project is relevant for the African Union's Agenda 2063 and the United Nation's 2030 Agenda and contributes primarily to the progressive achievement of Sustainable Development Goal (SDG) 7 of ensuring access to affordable, reliable, sustainable, and modern energy for all. Furthermore, it promotes progress towards SDG 5 (achieving gender equality and empowering all women and girls), SDG 9 (building resilient infrastructure, promoting inclusive and sustainable industrialisation, and fostering innovation), and SDG 12 (ensuring sustainable consumption and production patterns).

The EA-SA-IO region has considerable energy resources, yet most countries in the region experience energy supply challenges owing to inadequate level and coverage of physical energy infrastructure. These challenges will continue to grow, because most countries in the region are expected to see increased demand from economic and population growth. As such, there is an urgent need to address energy poverty, manifested through low access rates and reliance on traditional fuels such as charcoal. In addition to energy poverty, energy supply challenges also drive up the cost of doing business, negatively impacting the competitiveness of the region in its internal and external markets.

Under the ongoing ESREM project, regional harmonised legal and regulatory frameworks and synthesised renewable energy and energy efficiency programs in the EA-SA-IO region are being drafted. The results of the project, once adopted, are expected to stimulate regional integration, energy trade and investment in energy markets across the region.

The prices of variable renewable energy (VRE) have plummeted over the last decade, making large scale development of these technologies not only the most sustainable, but also the most economical choice for powering Africa's growth. A key enabler for this development will be well-developed and modern electricity grids that can securely and efficiently transfer power from where it is generated to where it is utilised.

In that regard, the ESREM project is publishing this guideline report to:

1) Provide the reader with an understanding of the attributes of different power generation sources and demand types as well as the technical and physical phenomena that may constrain grid capacity.

[1] The scope of the project includes 29 countries: *Angola, Botswana, Burundi, Comoros, Djibouti, DRC, Egypt, Eritrea, Eswatini, Ethiopia, Kenya, Lesotho, Libya, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Rwanda, Seychelles, Somalia, South Africa, South Sudan, Sudan, Tanzania, Tunisia, Uganda, Zambia, and Zimbabwe.*

2) Provide an overview of the structure of electric power systems in the EA-SA-IO region, as well as examples of typical capacity considerations that may be relevant in different types of systems.
3) Introduce grid capacity principles and apply them to the examples of representative power systems identified under the preceding point (point 2).
4) Propose harmonised guidelines for grid capacity considerations and integration of renewable generation to the grid, in the context of the topics covered in this report.

Disclaimer – it was initially envisaged that this paper would include a grid capacity assessment of four selected member states. Due to lack of data required for such studies, a different approach has been chosen whereby generic examples of power systems with attributes that should be relatable to the countries in the EA-SA-IO region are provided. Though each generic example will not provide a perfect match for any of the member states, this approach may prove more relevant for a larger number of the member states than simply modelling using concrete information from a limited number of member states.

2 Integrating VRE in Power Systems

Key chapter takeaway

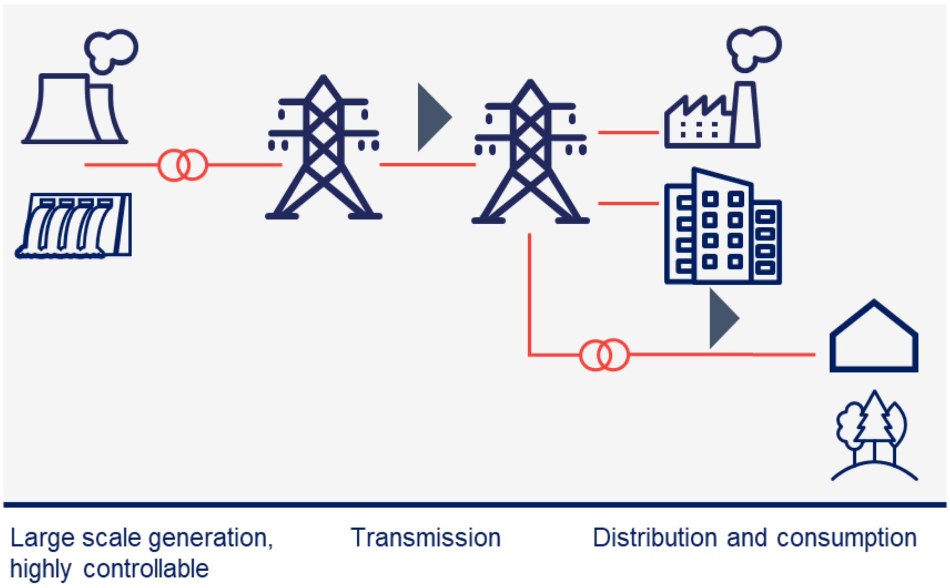
- **The renewable energy transition makes power systems more complex, less predictable, and more distributed in nature.**
- **To ensure safe and reliant electricity supply in the face of these challenges, measures to enhance flexibility and controllability become increasingly important.**
- **The impacts of VRE occur at all system levels, from distributed rooftop solar PV in local low-voltage grids, to large scale wind power plants connected at high voltage.**

An electric power system is a combination of connected electrical components used to supply, transfer, distribute and use electric power. Behind the socket in each grid connected household, store, and factory exists a vast network of lines, cables, transformers, and other equipment transporting the power generated from different power plants with diverse characteristics to exactly where electricity is needed at any given time.

2.1 Basic Structure of Electric Power Systems

The interconnected electricity grid is often referred to as the world's largest and most complex machine. However, the basic structure of traditional power systems may, at a high level be illustrated schematically as seen in the figure below.

Figure 2-1: Schematic lay-out of traditional power system

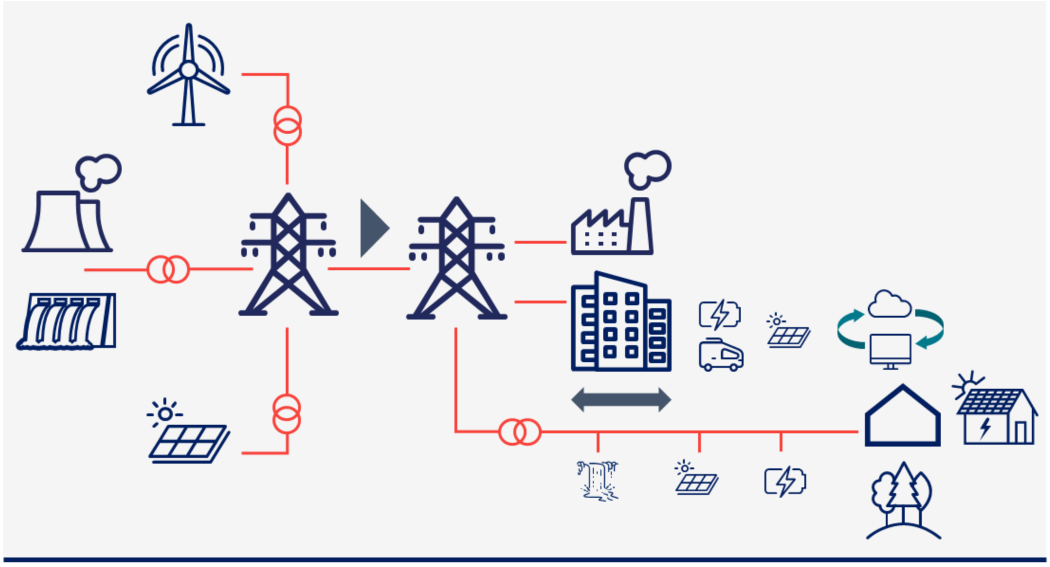


Source: Consultant

Large thermal power plants have traditionally been placed close to large load centres, while large-scale reservoir based hydro power are geographically bound and are therefore often located further away from large loads. In both cases the power flow is typically unidirectional (i.e., it flows from the power plant to the load centres).

The trend in modern-day power systems is towards increasing complexity, as indicated in Figure 2-2.

Figure 2-2: Renewables-based, distributed power system



Source: Consultant

The emergence of distributed energy generation such as rooftop solar has led to the coining of the term *prosumer*[2]. Transport is increasingly being electrified and smart meters and digitalisation means that power systems are facing more active end-users than before.

Power system operation is a balancing act. In order to maintain a stable and secure energy system the power fed into the system by generators must equal the power drawn from the system by load (plus losses) at all times. As generation is becoming more distributed and generation from variable renewable energy sources such as wind and solar increases, both the demand side and the operational patterns of the traditional power supply must adapt.

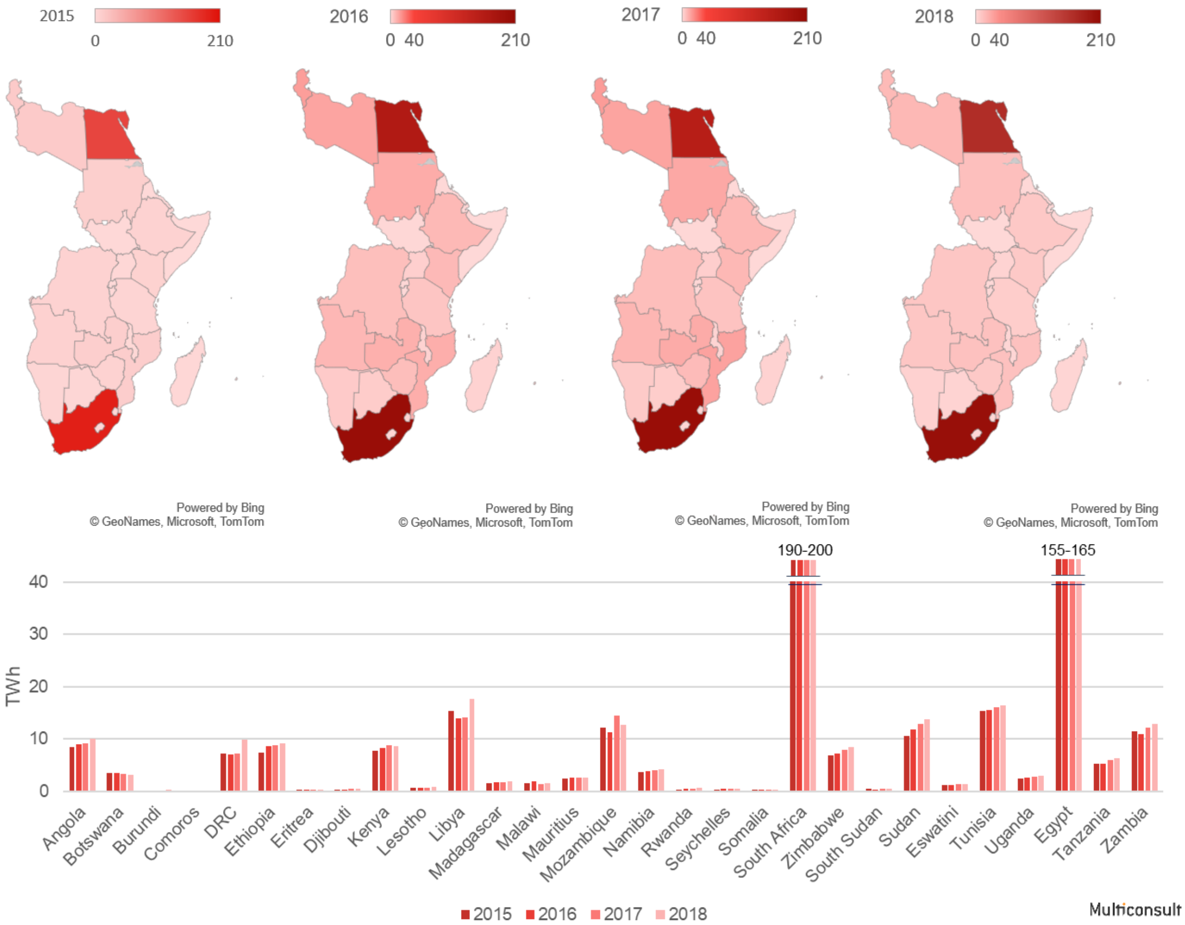
2.2 Demand Side

Electricity demand, often also referred to as *load* on the system is composed of a multitude of customers with varying requirements for electricity at any given time.

The final energy consumption in the EA-SA-IO region increased by nine percent from 476 TWh in 2015 to 519 TWh in 2018 (United Nations Statistics Division, 2021). Electricity gross demand, assumed to also include losses, is listed by the same source as 612 TWh in 2018 (United Nations Statistics Division, 2021). The four island states (Comoros, Mauritius, Seychelles, and Madagascar) had a total demand of approximately five TWh in 2018, while South Africa and Egypt alone constituted more than 70 percent of the 2018 energy demand, at 371 TWh.

[2] Prosumer: Someone that both consumes and produces – in power systems this refers to someone that both produces and consumes energy. The prosumer term is normally not applied on production facilities with some self-consumption for auxiliary systems; rather, it refers to typical energy consumers that also produce energy, though the production is not necessarily a primary objective.

Figure 2-3: Electricity – final energy consumption in the EA-SA-IO Region



Source: (United Nations Statistics Division, 2021)

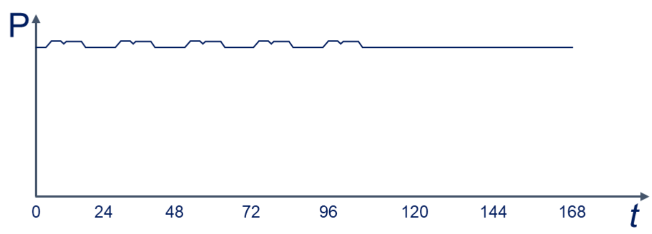
The Eastern African Power Pool (EAPP) and Southern African Power Pool (SAPP) master plans both foresee a continued growth in both peak load (MW) and energy demand (TWh), partly due to suppressed demand resulting from low installed capacities and unreliable supply.

2.2.1 Classification of Demand

Electricity demand profiles, or load curves, vary among groups of customers. This section presents a high-level classification which distinguishes between large industrial customers, commercial and public services, residential and agricultural demand. Electricity for transportation is also briefly described.

Industry

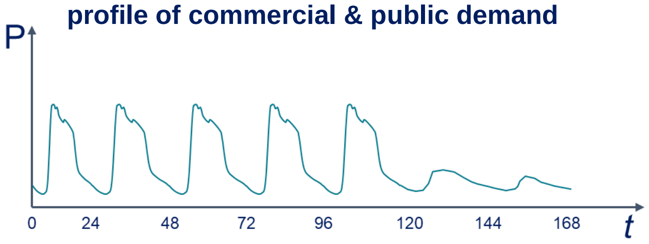
Figure 2-4: Schematic presentation of typical weekly profile of industrial demand



The industrial load curve of large power systems is normally dominated by energy-intensive industry with around-the-clock-operations. However, manufacturing and other daytime industries mean that there will be variations between day/night and over the week. Even so, the load curve for large-scale industry is typically relatively flat, with only minor variations over the day, week, and year.

Commercial & Public Services

Figure 2-5: Schematic presentation of typical weekly profile of commercial & public demand

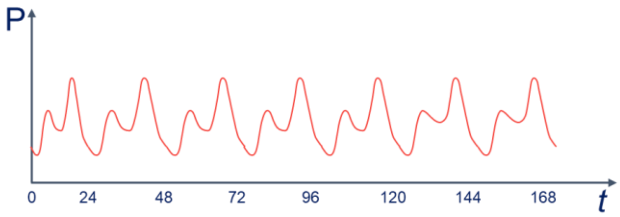


Commercial and public services include government facilities, shops, hotels, and so on. The main electricity consumption comes from lighting, heating, ventilation, air conditioning, appliances, and electronics.

The load profile typically follows normal business hours, with a rapid increase in the morning, a relatively flat load profile during the day (with a small dip around lunch hours) and a dip at night. Demand during weekends is typically significantly lower than during weekdays. Seasonality is generally low, however, climatic conditions may impact the need for cooling.

Residential

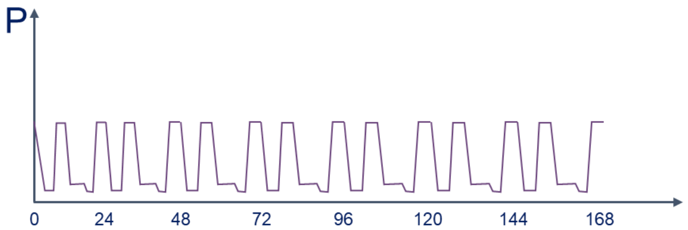
Figure 2-6: Schematic presentation of typical weekly profile of residential demand



Residential customers account for significant portions of the total demand in most power systems. The largest sources of electricity demand are space heating and cooling (air conditioning) as well as lighting, water heating, appliances, and electronics. Although seasonality is less prominent than in other parts of the world, residential electricity demand in the EA-SA-IO region tends to be highest during the hot season, due to increased cooling requirements. Over the day and week, the demand typically has a clear morning peak when people are awake and prepare for their day as well as a distinct evening peak when people return to their homes, turn on the lights, and use appliances.

Agriculture

Figure 2-7: Schematic presentation of typical weekly profile of agricultural demand



Agricultural activities do not constitute a large share of the total demand in most African electricity grids. However, a recently published article (Giacomo Falchetta, 2021) points to the fact that more than 90 percent of total cropland in sub-Saharan Africa is rainfed and argues that the growth of renewable energy, particularly in the form of decentralised solar power could enable greater agricultural productivity across the Continent. For instance, by providing electricity to water pumps for crop irrigation.

Agricultural electricity demand varies greatly across seasons and cropping patterns. However, daily irrigation patterns tend to be dominated by irrigation pumps being switched on during night-time and during early mornings. Crop processing typically takes place during daytime, meaning that demand from irrigation and crop processing do not necessarily coincide.

Transportation

Electricity demand for transportation has historically been limited to railway, tramways, and metro systems. However, cost reduction and technological advancements in battery systems, as well as climate change mitigation policies are pushing the sector towards electrification.

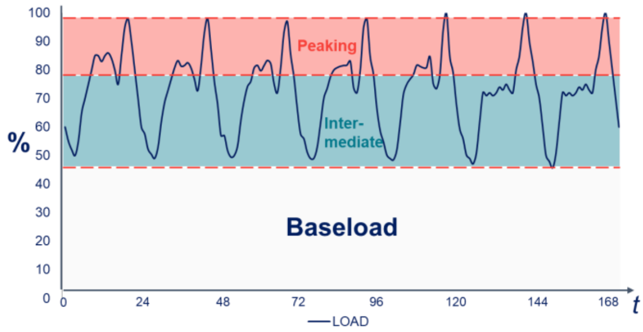
Although charging of electrical vehicles will introduce higher demand on the electricity grid, the batteries in the vehicles also represent distributed storage opportunities that could be utilised in periods of strained operation. At the local level, smart charging could help limit the need for investments in the distribution grid. In the transmission grid, the aggregated response from a large fleet of electric vehicles could contribute positively to sudden changes in grid operating conditions, hence facilitating increased share of variable renewable energy production.

Total System Demand

The total system load profile, or demand profile, is the aggregation of all the time varying loads in the system. In order to capture the total supply needed, total system load profile should also include losses in transmission and distribution.

The minimum load level that must be covered at all hours is often referred to as the baseload of the system. Peak load, or peak demand, describes the load level at hours of high consumption. The load level between peak load and baseload are normally referred to as the intermediate load level.

Figure 2-8 Schematic presentation of typical weekly profile of aggregated demand

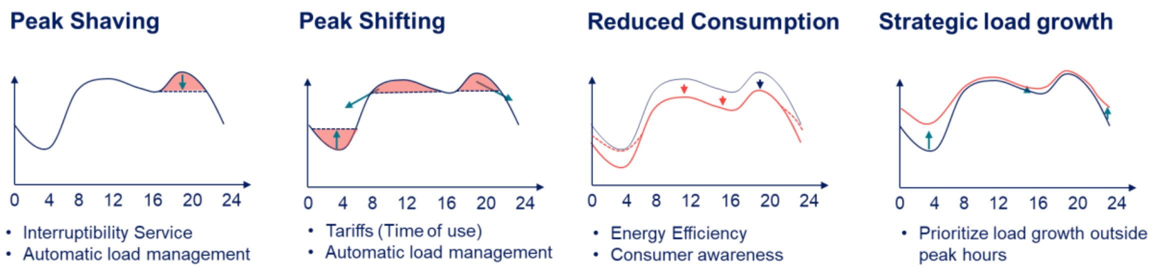


2.2.2 Demand Side Response

Traditional operation and planning in power systems has viewed demand as varying, but non-dispatchable. Therefore, while reducing electricity consumption long has been used as a reserve for maintaining the power balance in many African power systems, this has typically been done through costly and unpopular load shedding. In recent years, with the gradual increase of non-flexible power production as well as increased digitisation, demand side management has become increasingly relevant as a source of flexibility.

Energy demand management, also known as demand-side management or demand-side response, is the modification of the consumers´ demand for energy. Shifting the electricity consumption from hours of high load and prices to a more affordably priced time, means that the utilisation of the already existing grid capacity is improved. This may be a cost-efficient alternative to investments in increased transfer capacity, both at end-user level and for the national economy. This guideline report focuses on the technical issues related to grid capacity. Market initiatives for increased demand side flexibility are further discussed in another report produced under this assignment (see the guideline report on demand side management[3]).

Figure 2-9: Typical demand side response strategies



[3] Produced by CPCS, Econoler, and Multiconsult for the ESREM Project.

2.3 Supply Side

As highlighted in section 2.1, the generation fleet has typically been separated into baseload plants which are designed to run at a constant power output, and peaking plants that cover the load variations in the system.

Baseload plants are designed to generate large amounts of energy at relatively fixed output. They have limited cycling opportunities, i.e., they are typically slow-operating units with a low degree of flexibility in the power output. Thermal power plants and nuclear plants are typical examples.

Peaking plants have the opposite characteristics, as their objective is to follow the time-varying load. Such plants are typically able to start-up and alter the power output rapidly and are designed to operate smoothly even at low power output as compared to nominal power. Internal combustion generators and open cycle gas turbines are examples of traditional peaking units.

IRENA's flexibility report from 2018 (IRENA, November 2018) also describes a third class of generation plants: Intermediate generators that can be used to provide both base and peak load. Reservoir hydropower and modern combined cycle gas turbines are examples.

A common denominator for all traditional power plants is that they are all largely controllable assets, with predictable and/or controllable power output. Variable renewables do not fall into any of the above categories, because their power output is variable and to a certain degree, also difficult to predict.

Variable renewables are also by nature more distributed than the traditional large, centralised power plants. Small scale VRE enters the system at lower voltage levels, as seen from Figure 2-2. Rooftop solar PV is a good example of this, entering the system at the household level, typically at the lowest operating voltages, towards the end of the often radially structured distribution grid.

It follows that a large and rapid development of rooftop solar PV may risk overloading the local grid capacity. Grid hosting capacity assessments can be a useful tool to systematically assess such impacts of distributed energy resources. This approach allows utilities to assess how much solar PV (or other distributed power production) can be added to the various locations in the system before grid capacity violations become a concern and detailed interconnection studies should take place, and what requirements new production must face. Voltage regulation capabilities in the distributed plants can for instance have a big impact on hosting capacity.

As the net load[4] variation increases with higher VRE penetration levels, the need for flexibility in the surrounding power system also increases.

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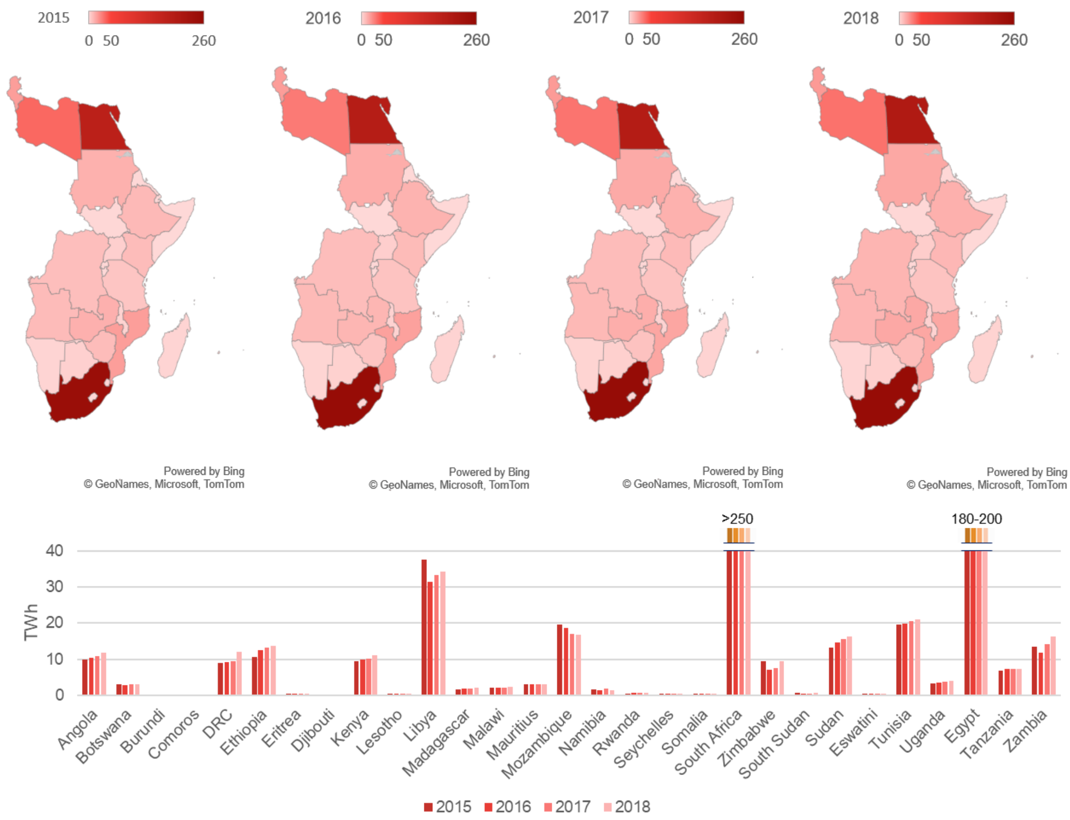
[4] Net load is the electricity demand minus generation from VRE, i.e. the electricity demand to be covered by dispatchable generators.

Table 2-1: Characterisation of power plants

	Baseload	Dispatchable	Variable
Renewable	• Geothermal • Biomass • Concentrated solar power (with thermal storage)	• Reservoir Hydro	• Wind • Solar PV • Run-of-river hydro • Concentrated solar power (without thermal storage)
Non-Renewable	• Coal • Nuclear • Gas • Liquid fuel	• Liquid Fuel • Gas	

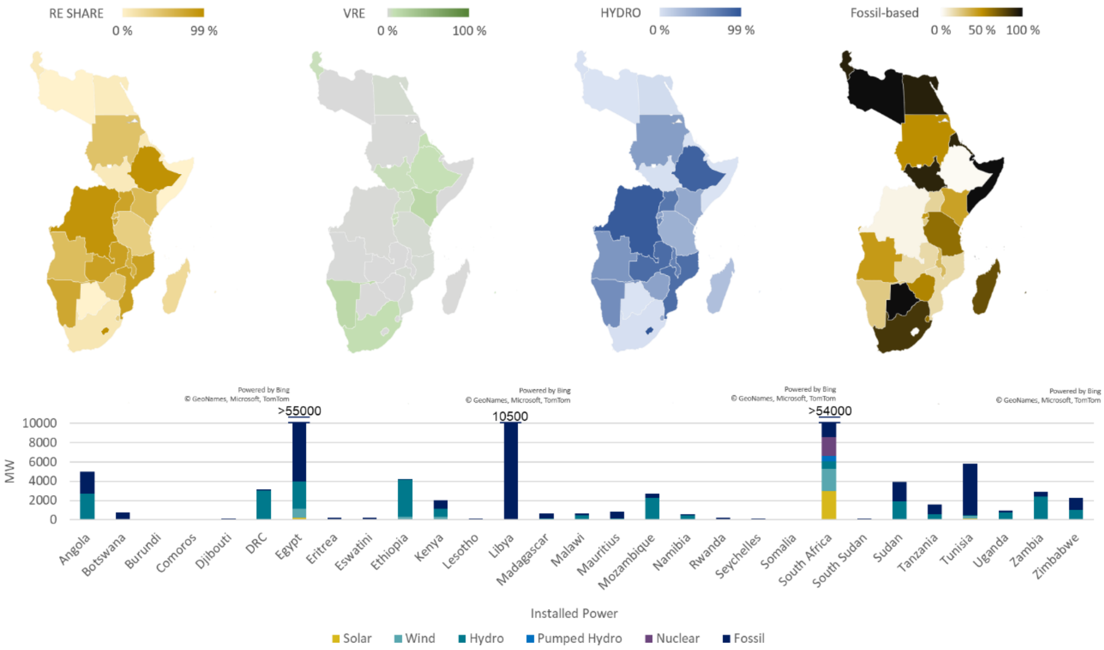
Total electricity generation in the EA-SA-IO region increased by seven percent from 607 TWh in 2015 to 649 TWh in 2018 (United Nations Statistics Division, 2021). More recent data is not yet available in the UN database.

Figure 2-10: Gross production of electricity (TWh) per country in the EA-SA-IO Region 2015-2018



Source: UN data retrieval system (data.un.org)

Figure 2-11: Installed generation capacity in EA-SA-IO-Region (2018)



Source: UN data retrieval system (data.un.org)

2.4 Storage

An important part of the grid capacity challenge is related to short-term fluctuations, like unexpected changes in VRE output, faults on given components in the grid, or demand peaks of short duration. Where grid capacity is insufficient, the traditional solution has been to increase transfer capacity by building more grid or increasing local production capacity by investing in peaking plants. Storage may provide a more cost-efficient alternative to such investments.

Over the ten-year period from 2010 to 2020, the cost of utility-scale lithium-ion battery storage has fallen by nearly 90 percent[5]. In fact, Bloomberg finds that the price of multi-hour lithium-ion batteries has fallen to a point where they are now competitive with fossil generation capacity, such as natural gas peaking plants when it comes to providing dispatchable power in many markets - even without subsidies.

Grid-sized battery energy storage systems can provide short-term backup and help reduce the transmission need for shorter durations of time. If designed correctly, the rapid response of modern-day inverter-based batteries means that they can also help stabilise the grid by reducing the need for voltage support, spinning reserves, and inertia response from rotating machinery.

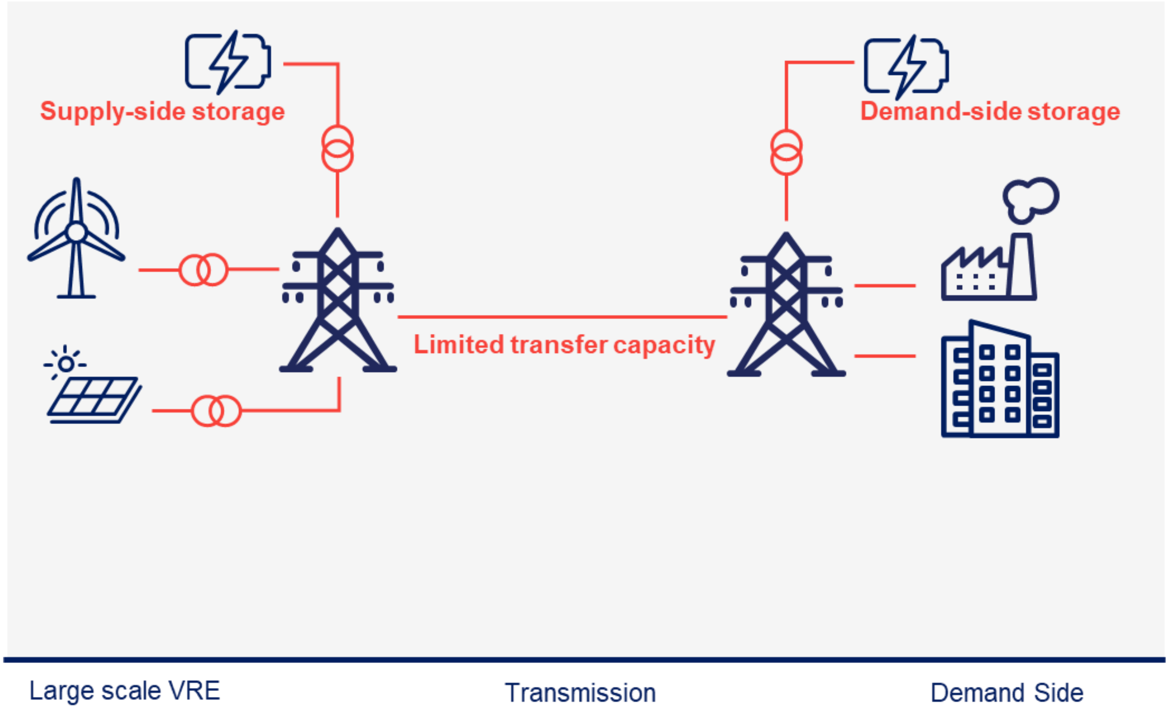
Virtual Power Lines

Batteries or other types of storage may also be used to manage transmission congestions without having to invest in grid reinforcements. By equipping constrained transmission lines with storage in each end, the sending side may store power that cannot be transmitted due to capacity constraints. The receiving side storage system may be charged when transmission capacity is sufficient and be used to meet demand in periods with insufficient transfer capacity. This solution is often referred to as Virtual Power Lines. These may for instance be used to

[5] https://www.bloomberg.com/news/articles/2020-12-17/this-is-the-dawning-of-the-age-of-the-battery

facilitate large-scale integration of VRE with peak power above maximum transfer capacity, without an immediate need for grid reinforcements, as illustrated in the figure below.

Figure 2-12: The concept of virtual power lines - example for VRE implementation



Source: Consultant, based on (IRENA, 2020)

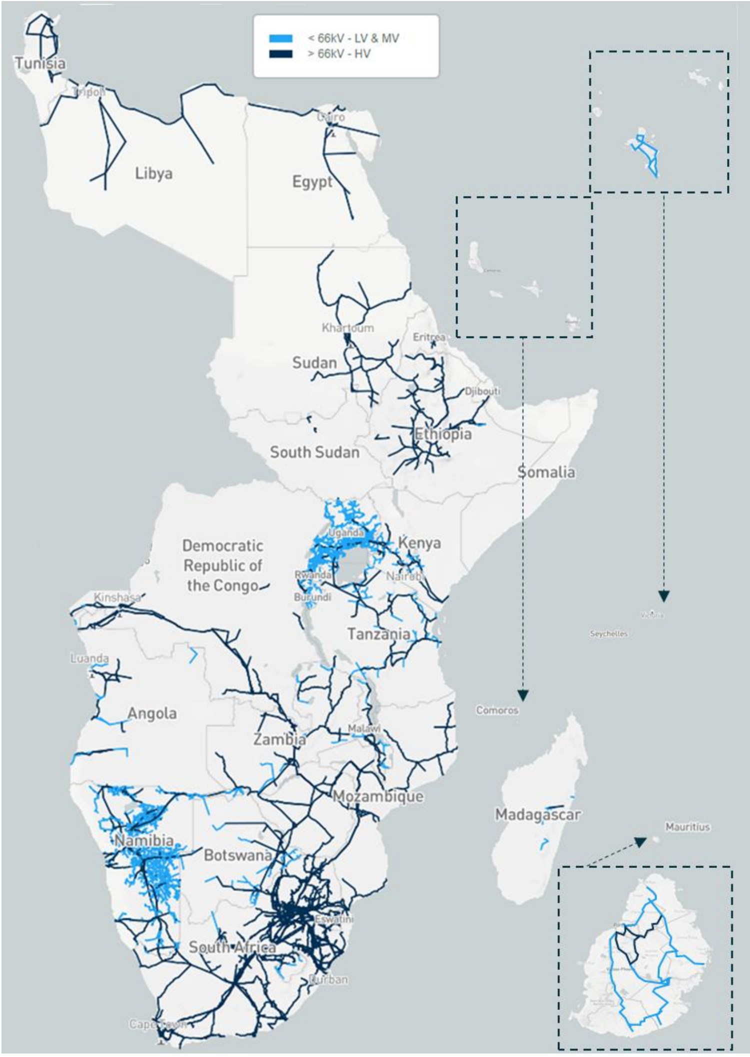
In addition to battery energy storage solutions, long term energy storage solutions also include compressed air, hydrogen fuel cells, and hydro reservoirs. Hydro reservoirs are currently the most available of these sources, but expansion is site dependent.

2.5 Transmission and Distribution

Transmission and distribution grids bind supply and demand together. Insufficient grid capacity can therefore be economically crippling on a local, national, and even regional scale.

Figure 2-13 below presents a high-level overview of the electricity grid in the region as of 2019, based on data from the World Bank Africa Electricity Grids Explorer. Although the grid explorer does not provide a 100 percent updated, complete, and accurate representation of the grid, and the varying level of detail across different countries indicates that the input data in the explorer varies from country to country, the figure provides the best available overall representation of the key structure of the transmission grid in the region.

Figure 2-13: Electricity Grid in the EA-SA-IO-Region (2019).



Source: Based on the World Bank Africa Electricity Grids Explorer (http://africagrid.energydata.info/). Grid data for island states based on consultant's own research.

As outlined in section 2.1, a traditional grid layout consists of large power plants connected to a transmission grid that carries the power at a high voltage (HV), often over considerable distances. The HV transmission grid is meant for bulk transmission. There are few customers directly connected to the transmission grid, mainly large industrial clients. Power is stepped down to regional or local distribution grids for further transmission and distribution. More developed transmission grids are typically meshed in structure in order to ensure safe and secure operation of the system even if one component fails. However, the establishment of a meshed grid structure is a techno-economic decision. In areas with low and/or non-critical demand it may not always be economically optimal to establish two transmission grid connections.

The distribution grid is often radial in structure. Its purpose has historically been to supply power to end users such as commercial and residential customers. Power flow has been unidirectional, in the direction from the HV system to the customers connected at low voltage. As more and more distributed power is developed, the distribution grid will go through a rapid transition from unidirectional power flow to a bidirectional power flow. In other words, rooftop solar, small hydro, and distributed storage are disrupting the traditional use of distribution grids described above. Transitioning from pure distribution to a multi-purpose grid can challenge grid capacity at the local level, and grid capacity assessments in distribution grids are becoming a lot more complex. Utilities should take an active approach to this transition.

In large and geographically dispersed power systems, a regional grid is used as a linkage between the transmission grid and the distribution grid.

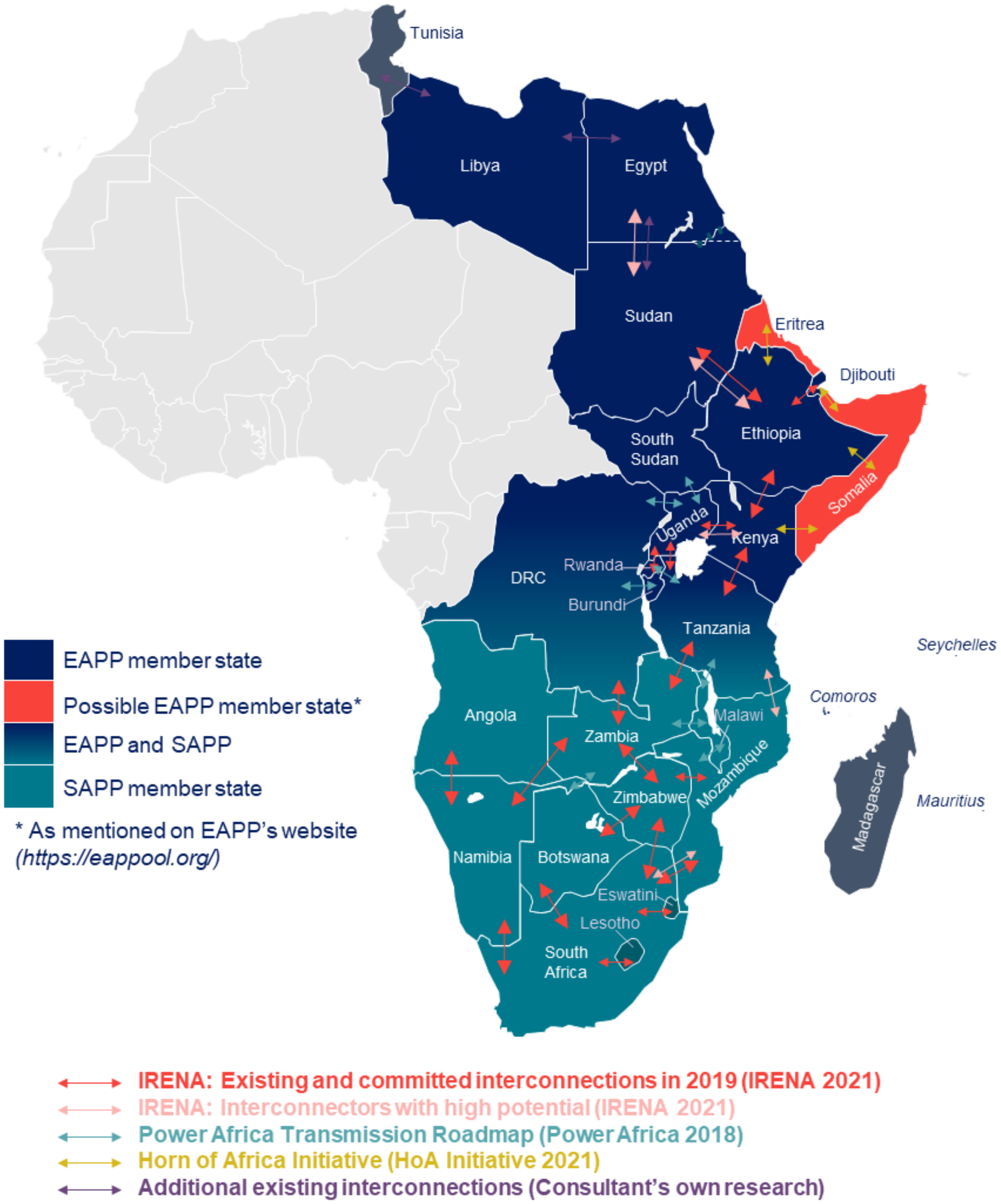
2.5.1 Cross Border Interconnectors

Cross-border interconnectors can facilitate power exchange between the different national power grids, and through that unlock underutilised trading potential.

The Power Africa Transmission Roadmap to 2030 (Power Africa, 2018) states that some countries have national supply surpluses and stranded assets while others face critical supply shortages. The lack of sufficient cross-border transmission capacity means that the ability for electricity to flow from surplus regions to deficit regions is severely constrained. Increased investments in cross-border transmission infrastructure projects should therefore lead to better balancing of the existing energy supply challenges and would also prove beneficial in catalysing a rapid rollout of renewables. The roadmap identifies more than 5000 kilometers of priority transmission lines that could help unlock regional trade in Eastern (~2,000 km) and Southern Africa (~3,000 km). The roadmap, however, also recognises that other cross-border projects are important to countries' economies, development, and energy sector sustainability. The full list of projects described in the report consists of more than 3,600 kilometers in East Africa and more than 5,600 kilometers in Southern Africa.

The below figure is a compilation of information from IRENA, (IRENA, 2021) Power Africa (Power Africa, 2018), and the Horn of Africa Initiative (HoA Initiative, February 2021) data, as well as the consultant's own research on the status and plans for interconnections in the EA-SA-IO region. Power pool membership is indicated by the colour of each country. As shown, there is a large number of proposed projects. Regional coordination is key to a sustainable, economically viable, prioritised grid development.

Figure 2-14: Existing, committed and proposed interconnectors in the EA-SA-IO region



Sources: Based on IRENA 2021, Power Africa 2018, HoA Initiative 2021, Consultant's own research

3 Managing grid capacity with increased VRE

Key chapter takeaway

- **Sufficient grid capacity is key to enabling the renewable energy transition**
- **Grid capacity does not only refer to transfer capacity of the transmission and distribution grid, but also includes operational requirements on the supply (and demand) side.**
- **Grid flexibility becomes increasingly important as VRE deployment continues to increase**
- **Distributed renewables such as rooftop solar PV mean that grid capacity at the local and regional level becomes more important**
- **Renewable power plants may, when well designed, be well suited to alleviate grid capacity constraints**

Grid capacity can be defined as the electricity grid's ability to receive, transport and supply power at all times. Numerous aspects and characteristics of the electricity grid impacts this capacity. It is important to highlight that grid capacity is not one single, centralised parameter of the power system. While local capacity constraints may hinder the connection of a single customer or power plant but have little impact on the power system at large, central, or regional constraints may limit the opportunities for development of entire regions or countries. It follows that grid capacity can refer to the ability to accommodate a new power plant or a new load in a single point in the system, or it may refer to the grid's capacity for bulk transmission between areas or across country borders.

The technical limitations to current carrying capacity in components of the grid (e.g. power lines) may depend on ambient conditions, meaning that seasonal variations in grid capacity are common. Operating requirements also impact how grid capacity is viewed. A common way to present grid capacity is to indicate the capacity with the most critical component disconnected, as well as presenting it with all components intact and connected.

Supply capacity refers to the ability of the installed generation capacity to meet demand as it varies from minimum to maximum values over time. Available generation capacity in the system must cover demand at all times to avoid load shedding. The system must also be able to handle sudden changes in the balance between supply and demand, meaning that some reserves are necessary in operation. Traditionally, this balancing act has been addressed on the supply side.

Several terms are used to describe the electricity grid's ability to accommodate new generation. When assessing grid connections of new power plants, *power evacuation capacity*, *grid hosting capacity,* and *maximum export capacity* are all commonly used terms that refer to the connected transmission and distribution grid's ability to safely receive and evacuate the power.

The equipment rating of components in the transmission and distribution grid indicates how much power the system can transmit safely and securely. The ability to transfer power from one part of the grid to another, through one or more connectors, is often referred to as (net) *transfer capacity*. The ability of the electricity grid to deliver power to all consumers is often referred to as *delivery capacity*.

In order to properly assess grid capacity, one must often study the *power system reliability*. Increased VRE penetration from wind, large-scale and distributed solar, which depend on insolation and wind strength, complicates the traditional mode of operation.

This chapter provides a brief introduction to the topic, focusing on the implications for scaling up VRE.

3.1 Technical Capacity Limitations

The transmission and distribution grid should be able to receive and transmit power and meet demand during all hours of the year. The power should be transmitted and delivered at a quality that is satisfactory to all customers. Capacity considerations should therefore be made based on the conditions prevailing when the system is most strained. This may occur during demand peaks or during hours of high production.

Equipment connected to the electricity grid is designed to operate within a specified bandwidth of frequency and voltage. Failure to comply with the design limits may endanger or damage equipment, and in severe cases also humans.

Although not described further in this report, the quality of the power supply is also important. Due to the inherent technical characteristics of all equipment that is connected to the power grid, there is always a certain amount of noise/disturbance on the power that is delivered, often referred to as flicker and harmonics or harmonic distortion in power system terminology. These distortions should be kept within specified limits in order to avoid damage to equipment.

Equipment Ratings

Equipment ratings include the thermal capacity limits and rated short-circuit withstand capabilities of breakers, busbars, transformers, lines, and cables in the system. Failure to stay within these limits may cause damage to equipment. Components in the power system are normally protected, which means they will trip in conditions outside their defined operational range. The uncontrolled tripping of critical components in the power system may compromise system integrity and lead to power outages, or in severe cases blackouts of large areas, and should be avoided if possible.

Overhead lines are designed with requirements to maximum allowable conductor temperature. A thermal overload occurs whenever these design criteria are exceeded.

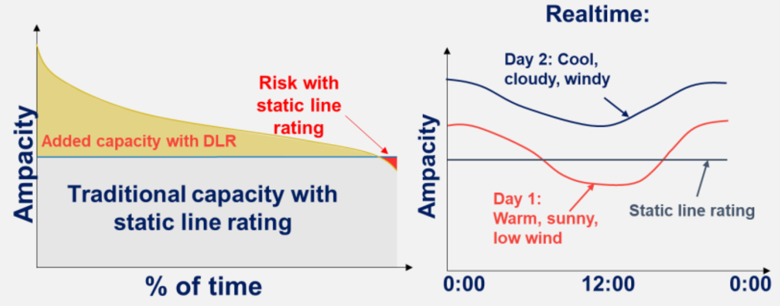
The current carrying capacity (ampacity) of an overhead line is decided by the choice of conductor material and cross-section, as well as the physical geometry of the transmission. External factors influencing the conductor temperature, and as a consequence also the ampacity of the overhead line, include solar irradiation, wind speed and wind direction, and the ambient temperature. The ampacity is decided by the most critical portion of the line (i.e. the weakest link).

Cable ampacity is even more dependent on the cable-laying geometry and also depends on the choice of cable insulation. External factors determining the conductor temperature (ampacity) are related to the heat transfer away from the cable and include soil thermal resistivity and soil temperature.

Overheating may cause an accelerated aging process and deterioration of mechanical tensile strength. Operational hazards caused by overheating of overhead lines are mainly due to increased sag, which causes increased risk of short circuit events, damage to material and most importantly, damage to persons.

Dynamic line rating, also known as real-time thermal rating, is an electric power transmission operation philosophy aimed at enhancing the utilisation of the existing grid capacity, without compromising safety. By combining real-time weather data, conductor condition measurements and advanced weather forecasts, dynamic line rating has proven to increase allowable transfer capacity. This can reduce grid congestion and, therefore also curtailment, hence possibly enabling an accelerated transition to a greener grid.

Dynamic line rating refers to the active varying of presumed thermal capacity for overhead power lines in response to environmental and weather conditions. This is done continually in real time, based on changes in ambient temperature, solar irradiation, wind speed and wind direction, with the aim of minimising grid congestion (IRENA, 2020).



Several grid operators have tested dynamic line rating with positive results. There are clear indications that the increase in ratings can improve the cost-effectiveness of the generation dispatch, and also boost integration and reduce curtailment of solar and wind power (IRENA, 2020).

It is important to note that transmission lines that are not congested, or do not limit market activity (where applicable), may not benefit fully from dynamic line rating. Similarly, power systems that are constrained by voltage, stability, or substation limitations may not benefit. Therefore, utilities should take an active planning approach where they have identified critical lines and consider dynamic line rating to its alternatives before implementing it.

Finally, it is worth noting that the initial entry cost of implementing dynamic line rating is significantly higher than the marginal cost of expanding it, because the first intervention will entail the setting up auxiliary systems for control and software for data monitoring, and training of personnel.

IRENA lists three key enablers for implementation of dynamic line rating:

1. Algorithms to calculate ampacity
2. Digitalisation for real-time monitoring, communication, and control
3. Securing regulatory incentives for cost-efficient grid operation

Voltage Requirements and Reactive Power Capacity

The voltages in a power system describes the potential to transmit power from one point in the system to another. It is analogous to pressure in a water pipe. Just like water flows from a point with high pressure to a point with low pressure, power flows from a point with high voltage to a point with lower voltage.

Just like the current, the voltage of the system oscillates at the system frequency. In large AC power systems, the alternating voltage and alternating current may, for a number of reasons, come slightly out-of-sync. This reduces the ability to convert the electrical power back to useful work in machines and equipment. The term *reactive power* is used to describe this phenomena. Reactive power, like real power, must always balance (that is the reactive power produced on a system must equal the reactive power consumed). Reactive power can be supplied from the generators; however, it is often more economical to supply such power from voltage regulating distributed throughout the system.

Voltage control in an electrical power system is important to ensure safe and proper operation of electrical power equipment. Failure to control the voltage may lead to damage such as overheating of generators and motors or shortened lifespan of light bulbs and residential appliances or damage to the insulation of equipment if operated above their rated insulation level. From an operational perspective, voltage control is important in order to reduce transmission losses and to maintain the ability of the system to withstand and prevent voltage collapse.

Equipment for Voltage Regulation

Reactors consume reactive power and reduce voltage.

Capacitors produce reactive power and raise the voltage. Traditionally, capacitors and reactors are switched by circuit breakers, resulting in moderately large steps in reactive power. Moreover, the reaction time is relatively long.

Rotating phase compensators are electrical machines with no prime mover i.e. not producing active power.

Static var compensators can be used for faster voltage control but are significantly more expensive than reactors and capacitors**.** They operate by switching in reactors and capacitor batteries using thyristors as opposed to circuit breakers, thus the equipment can be switched in / out in a single cycle (0.02 seconds).

Static synchronous compensators can also be used for faster voltage control. They are based on technology using transistors (IGBT) – and provides very fast control (even faster than static var compensators) and can control active and reactive power fully decoupled.

Generators may produce or draw reactive power, defined in their capability diagram. VRE production from wind and PV are often based on IGBT technology and may provide static synchronous compensators-functionality if required.

Frequency Control

A key characteristic of the power supply in the electric power system is that it comes in the form of AC (alternating current), i.e., the current alternates between positive and negative value. The frequency of an AC power system describes how many such oscillations occur every second. In a 50 Hz system, the alternating current oscillates 50 times a second. The frequency of an interconnected power system must be consistent in order to avoid damage to equipment, which is normally designed to operate at a very narrow band around the nominal system frequency.

Electric motors, for example in factories, run at speeds which depend on the system frequency. Also, loads in the system may not have a linear relationship between power and frequency. In electric fans with speed being proportional to the torque the power is proportional to the speed squared. In other words – a small deviation in frequency may lead to a large deviation in power.

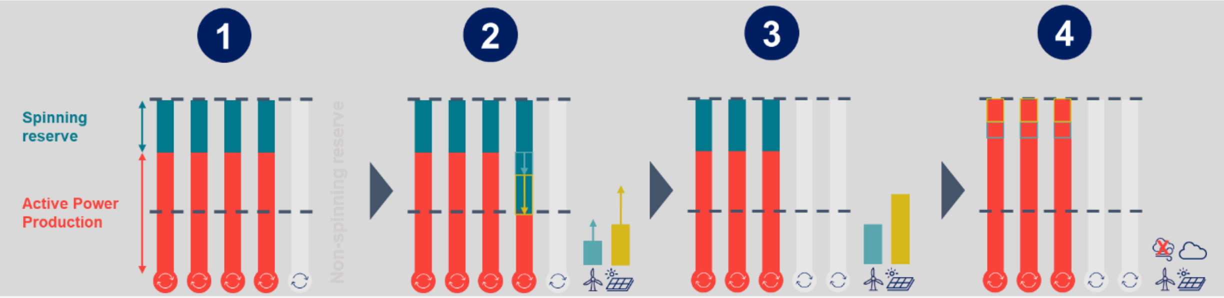
Power system operation is a balancing act. If supply and demand is not exactly balanced, it affects the frequency of the grid. When a step change in load is not instantaneously matched by a step change in power, the imbalance in the system is handled by the rotating machinery. This is referred to as *inertial response.* An increase (or decrease) in load will mean that the generators in the system slow down (or speed up) until electric power output is restored at a level that exactly matches demand. Maintaining a narrow band for frequency control is important in order to ensure this balance and avoid hunting: a phenomenon where increased load causes lower frequency, which again causes a fall in load, leading to a rise in frequency, which finally results in undamped oscillation with ever-increasing deviations from the nominal frequency.

Small changes in the supply/demand-balance in the power system occur continuously and are handled by inertial response. In order for the power system to be able to respond to larger disturbances, the generation fleet must include sufficient **spinning reserves**.

How added VRE may lead to inadequate spinning reserves

As VRE penetration rates increase, the availability of spinning reserves in the system may become an issue, as illustrated in the example figure below. The figure is generic but illustrates the importance of planning and maintaining control of grid operations.

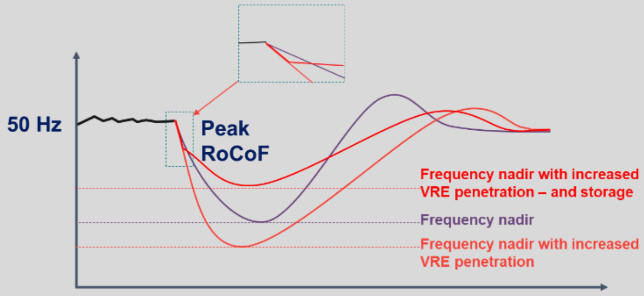
1) A system initially operating at a certain state experiences added VRE generation from wind and solar.
2) Adding VRE to the system means replacing power production from the existing rotating machinery in dispatchable power plants.
3) At a certain level, units may have to shut down in order to make room for the variable power production. This reduces spinning reserves by uploading the remaining power plants, and reduces the inertia of the system, making it more vulnerable to frequency deviations.
4) Without sufficient spinning reserves, the system will not be able to handle a transition to cloudy and windless conditions. Nor would the system be able to handle the loss of the largest generating unit, which is a common operating requirement.



Reducing the amount of traditional, rotating, dispatchable resources in the system not only reduces spinning reserves, but also decreases the inertia in the system. The fact box below demonstrates how this may impact the system's response to disturbances. Long term frequency stability issues may be a more complex situation with timescales up to minutes, corresponding to the response of devices such as load voltage regulators or prime movers.

The Impact of VRE and Storage on Frequency Response to Disturbances

Whenever a disturbance occurs, an imbalance between supply and demand leads to a change in the system frequency. This change must be arrested and reversed to avoid a system failure. Short term frequency stability issues can for instance be the formation of an under-generated island with insufficient under-frequency load shedding, causing a blackout of the system within seconds. The time-frame of interest is from hundreds of milliseconds up to seconds.



The most important aspect of frequency behavior following the sudden loss of generation is the point at which frequency is arrested - the *frequency nadir*. The inertial response from rotating machinery provides instant frequency stabilisation which limits the rate of change of frequency on the system. With increasing VRE penetration replacing rotating machinery, the inertial response will decrease, and the nadir may drop below the highest setpoint of under-frequency load shedding, i.e. the primary frequency control reserves are inadequate. This means that there will be constraints on the upper bound of the share of VRE plants in the system, often referred to as the maximum penetration rate or system non-synchronous penetration rate.

Although battery energy storage systems are not able to provide instantaneous inertial response and reduce the rate of change of frequency, they may provide very rapid power response, often referred to as "*synthetic inertia*". The batteries respond as soon as they are able to detect the event, normally in the hundreds of milliseconds-timeframe. This rapid response may be comparable or even superior to the fast frequency response of traditional rotating machinery when it comes to reducing the maximum frequency deviation.

3.2 Power System Reliability

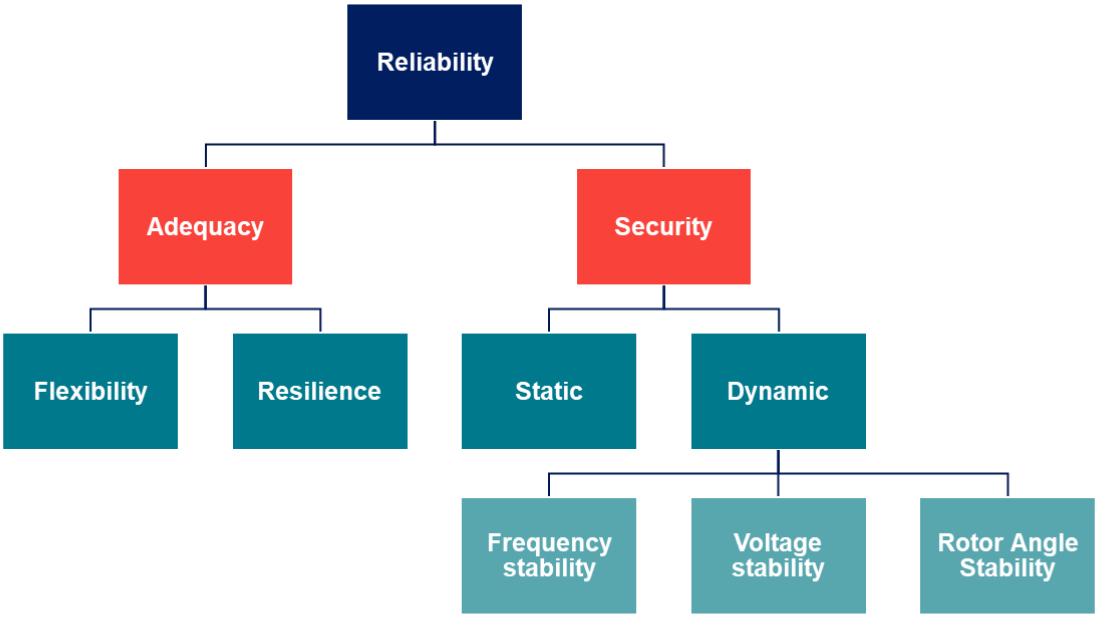
Power system reliability denotes the ability of the power system to supply adequate electrical service with few interruptions over an extended time period. In order to estimate reliability indices, one must be able to predict the system behavior. Reliability can be addressed by studying two basic functions of the power system, namely adequacy and security.

Power system security describes the ability of a power system to survive disturbances without the interruption of service. *Power system adequacy* is the ability of the power system to supply the electric power demanded by the customer at all times, accounting for possible outages of system components.

While security includes time-varying issues that can be judged by studying the performance of the power system under a particular set of conditions, for instance by using simulation tools, there is a need for probability distributions and consequence analysis when performing adequacy analyses.

A common classification of power system reliability is illustrated in Figure 3-1.

Figure 3-1: Classification of Power System Reliability



3.2.1 Adequacy

Adequacy is the ability of the power system to always supply the electric power demand, accounting for possible outages of system components. System adequacy includes both generation adequacy and transmission adequacy.

Generation adequacy of a power system is an assessment of the ability of the installed generation capacity to match the consumption of the power system. *Transmission adequacy* of a power system is an assessment of the ability of a power system to manage the flow resulting from the transfer of power from the generation to the consumption. The European Commission (Mercados, E-Bridge, & REF-E, 2015) describes adequacy as impacted by numerous random and non-controllable variables:

- Unexpected outages of generation or transmission facilities
- Availability of primary resources, mainly in the case of intermittent power from VRE
- Transmission capacity limits and availability
- Variability of the load
- Support (or lack of support) from neighbouring countries

Cross-border capacity, intermittent generation and demand response must be considered to obtain a realistic adequacy assessment

An important reliability issue is related to the capacity margin[6] of the generation fleet. There must be enough installed capacity in the power system to cover the peak load, and available capacity must continuously be equal to, or higher than, the demand. This includes withstanding outages of major facilities, extreme dry periods, or possible shortages of fuel availability. Adding VRE to the power system means that the installed power and produced energy increases, i.e., the

[6] Capacity margin describes the ratio of available generation capacity to peak demand, expressed in percentage terms.

availability of generation increases. However, dry (hydro), cloudy (solar PV), and windless (wind power) periods must be considered in the availability assessment.

Based on the above description of adequacy, one may describe adequacy by looking at the flexibility and resilience of the power system.

Flexibility

The flexibility of a power system describes its ability to accommodate changes in supply and demand at all time scales. Flexibility assessments include studying system response to changes, short-term uncertainty, and deviations between forecasts and actual energy delivery. That is: whether and how fast the system is able to restore the balance. In a VRE context, changes are typically due to the shadowing of solar plants or unexpected lulls of wind. The active power reserves and ramp rates of alternative plants and/or storage elements in the system must be able to handle the intermittent output from wind and solar unless load shedding is accepted. While wind and solar are considered inflexible production sources, other renewable sources such as dispatchable hydro power may introduce additional flexibility to the system.

Resilience

Resilience denotes the ability of the power system to respond to severe events such as the long-term outage of a cable, or absence of a resource such as fuel for diesel generators. Causes of resilience events may be natural or man-made.

It is noteworthy that, in recent years, with climate change, the frequency, severity and cost of weather-related natural disasters have been increased (Raoufi, Vahidinasab, & Mehran, November 2020). Also, literature suggests that future climate change could reduce water availability, and that diversifying generation portfolios with VRE could improve energy security, especially in hydro dominated power systems (Habostad, 2021)

Operators in well-developed power systems often plan the grid according to the N-1-criterion. For an N-component power system to fulfill the N-1-criterion, the system must be resilient by withstanding the loss of any of its components and still be in a stable steady state operation mode. In practice, this means that the disconnection of the largest power plant or the most critical transmission line in the system should not cause the disconnection of any consumer. The criterion can be checked by defining a certain number of contingencies that have a significant likelihood of occurring, and study how these will affect the system by simulating it in a power system simulation tool.

3.2.2 Security

Power system security denotes the ability of a power system to withstand disturbances without the interruption of customer service. To be secure, in addition to being stable, the system must be protected against contingencies that are not classified as stability problems. These include sabotage, fall of transmission towers, or the failure of a cable. Also, security includes the consequences of instability. Two systems may both be stable and have the same stability margins but be unequally secure because the consequences of instability are more severe in one system than the other.

Power system security is normally studied by performing static and dynamic security analyses. The assessment of system security allows the definition of important parameters for system operation such as the maximum admissible flow in transmission lines, the quantity of necessary primary, secondary, and tertiary frequency reserves, and reactive power requirements to control voltages in the system.

Steady state security

Steady state, or static security assessments include load flow studies of the system in normal operating conditions and with one or more components out of service. It is used to inform the definition of operational parameters such as the maximum admissible flow in transmission lines, and reactive power requirements for voltage control.

(Wu & Kumagai, 1982) define a steady-state security region as “a set of real and reactive power injections (load demands and power generations) for which the power flow equations and the security constraints imposed by equipment operating limits are satisfied.”

Stability

Power system stability is similar to the stability of any other dynamic system and is based on the same fundamental mathematics. It is simply an issue of preserving the equilibrium between opposing forces. In power system studies, the term stability denotes the ability of a power system to withstand sudden disturbances such as short circuit events, loss of a generator, transmission line or load, and regain a state of operation equilibrium so that the system integrity is preserved. This refers to meeting voltage and frequency requirements for the power system and may also include assessments of low voltage ride through capabilities and rotor angle stability for rotating power plants.

Power system stability is often divided into three categories:

1. **Frequency stability:** Balance between electric power supply and demand – maintaining synchronous speed of the generators in the system
2. **Voltage stability:** Reactive power balance
3. **Rotor angle stability:** Balance between mechanical torque applied to generators and electrical torque seen in the grid – maintaining small deviations from synchronous speed in all generators in the system

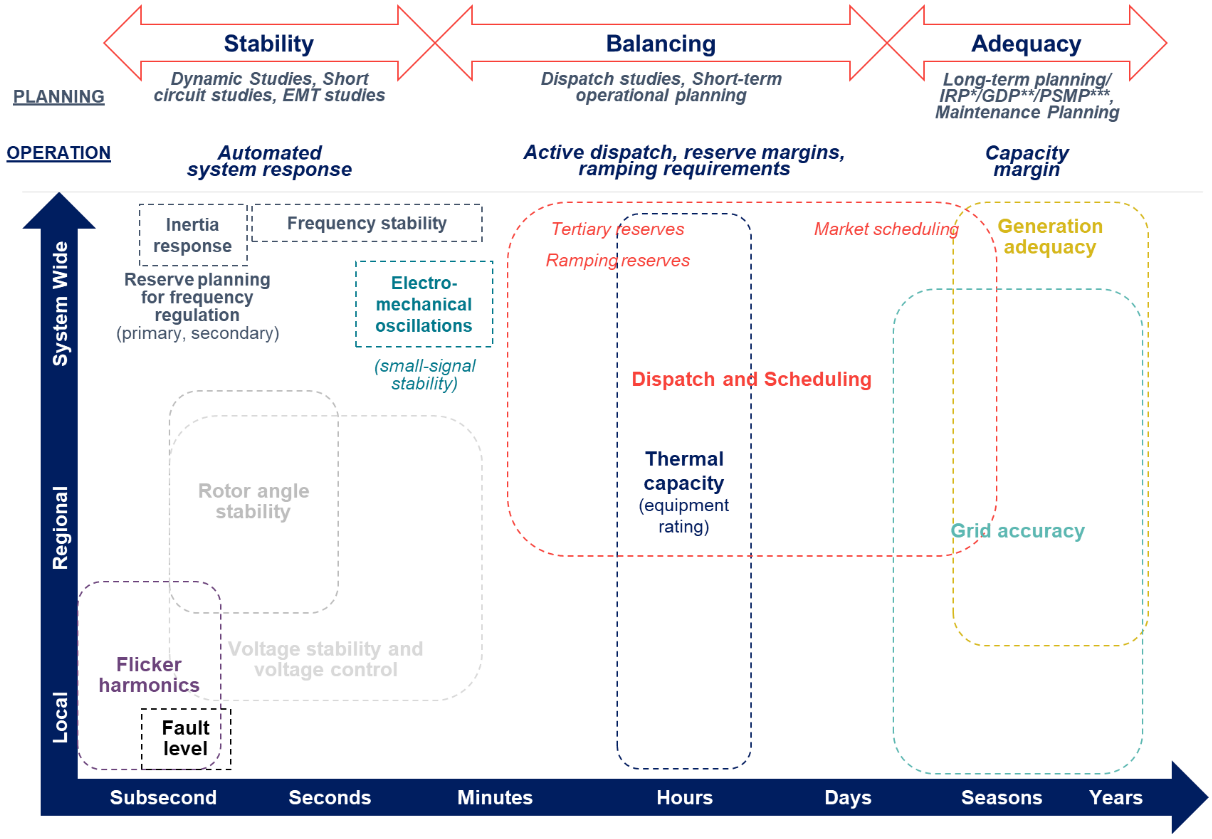
Hydropower and geothermal plants include rotating machinery which must operate at the same frequency as the rest of the system (i.e., with a constant synchronous speed). Solar PV and most modern wind power plants are grid connected through an inverter and are decoupled from the grid frequency – i.e., they have no synchronous speed. However, they may still impact frequency and rotor angle stability in the system by affecting the operation of the already existing plants in the system.

3.3 Planning and operational criteria for grid capacity

The planning and operation of the electricity grid is a complex task, encompassing numerous concerns. Operational challenges vary in terms of timescales and areas affected.

The below figure is based on the report “Bringing variable renewable energy up to scale” (Romero & Hughes, February 2015), and builds on concepts from the two preceding sections (i.e., power system phenomena to consider when assessing grid capacity).

Figure 3-2: Power System Operations and Planning Concerns



Source: Adapted from figure 2.6 and 2.10 in (Romero & Hughes, February 2015)

Increased share of VRE may impact the system from the local to the system-wide level, and at all time scales. At the local level in the sub-second timescale, for example, distributed or rooftop solar may have poor voltage control that results in negative impact on voltage stability and voltage control. Introducing a large amount of distributed power production to the power system can also impact fault levels. Power system protection initially designed to function in a distribution system where the direction of power flow (and fault currents) was unidirectional from the feeding transformer station to the end users may face challenges in detecting and clearing faults as power flow becomes bidirectional.

Without proper design requirements, the inverter-based distributed generation may also cause flicker and harmonic distortion that reduce the power quality.

Stability issues, as described in section 3.2.2 are phenomena in the time range up to seconds. Stability measures in power system operation are automated. This means that planning for stability issues is done by analysing events that may occur in the system such as large disturbances, and short circuits. The automated response of protection systems, controllers and regulators in the system is based on settings that are derived from the studies.

Balancing issues in the minute/hour to day timescale are planned through dispatch studies and by assessments of the necessary reserve margins and ramp rates of the supply side, available flexibility in the demand side, and potential congestion issues that may arise in the transmission grid. Static security analyses (load flow and dynamic studies) inform operators by providing transfer capacity limits which may not be violated, meaning for instance that generators close to large load centers must operate. This may put restrictions on VRE, causing curtailment on capacity located far from load centers and without sufficient transmission capacity.

At longer timescales, planners must ensure sufficient availability of power at all times, accounting for seasonal variations in both supply and demand. Power system adequacy is handled by long term planning, focusing on the availability of generation resources and the grid. Such planning is often carried out in the form of large system studies that consider existing and planned development in all supply, demand and transfer resources in the power system. Examples include integrated resource plans, grid development plans, or power system master plans.

4 Country specific considerations

Key chapter takeaway

- **Four generic examples of power systems with varying attributes are presented, representing four categories in which the countries of the EA-SA-IO region may be placed**
  1. **(Indian Ocean) island states**
  2. **Fossil based, developed power systems**
  3. **Partly renewable, intermediately developed power systems**
  4. **Systems with limited size, consumption and/or renewables share**
- **Issues and measures to be considered vary slightly between the four categories. However, flexibility and proactive planning to ensure transfer capacity at all levels are important for all categories**

Disclaimer: **It was initially envisaged that this paper would include a grid capacity assessment of four selected member states. Due to lack of data required for such studies, a different approach has been chosen. Generic examples of power systems with attributes that should be relatable for the countries in the EA-SA-IO region are provided. Examples are based on attributes of the various power systems in the EA-SA-IO-region.**

This chapter aims to provide examples of generic power systems that represent the situation in the various EA-SA-IO states. In order to provide examples that may be relevant for all member states, the chapter first sorts the national power systems in the region based on a select few attributes. Trying to capture all member states through a few select examples means that the chosen attributes are at a high-level and that all idiosyncrasies of the different power systems are not captured. Even so, this approach will be more relevant for a larger number of the member states than simply modelling a small number of concrete power systems in detail.

4.1 Categorisation of Countries in the EA-SA-IO-Region

Note on methodology: A number of parameters can be used to classify power systems. The categorisation presented in this sub-chapter of the report focuses on a few select performance indicators. The categorisation is based on UN statistics, but to a certain degree also includes qualitative assessments made by the Consultant. The following attributes have been used to separate key characteristics of the power systems:

1. **Renewable energy share:** Renewable energy share (as percentage of installed capacity) is used as an indicator of how far the country has come in developing a low-emissions power system.

2. **Electrification rate:** The electrification rate is chosen as an indicator of how far on the way to universal energy access to electricity the country is. It may also, indirectly, be an indicator of the geographic reach of the grid.

3. **Total electricity consumption:** Total electric energy consumption describes the size of the existing power system and is therefore an indicator of how large an impact VRE may have in the short term.

4. **Electricity use per capita:** Electricity use per capita indicates not only the amount of people with access, but also the degree to which the country uses electricity for productive purposes.

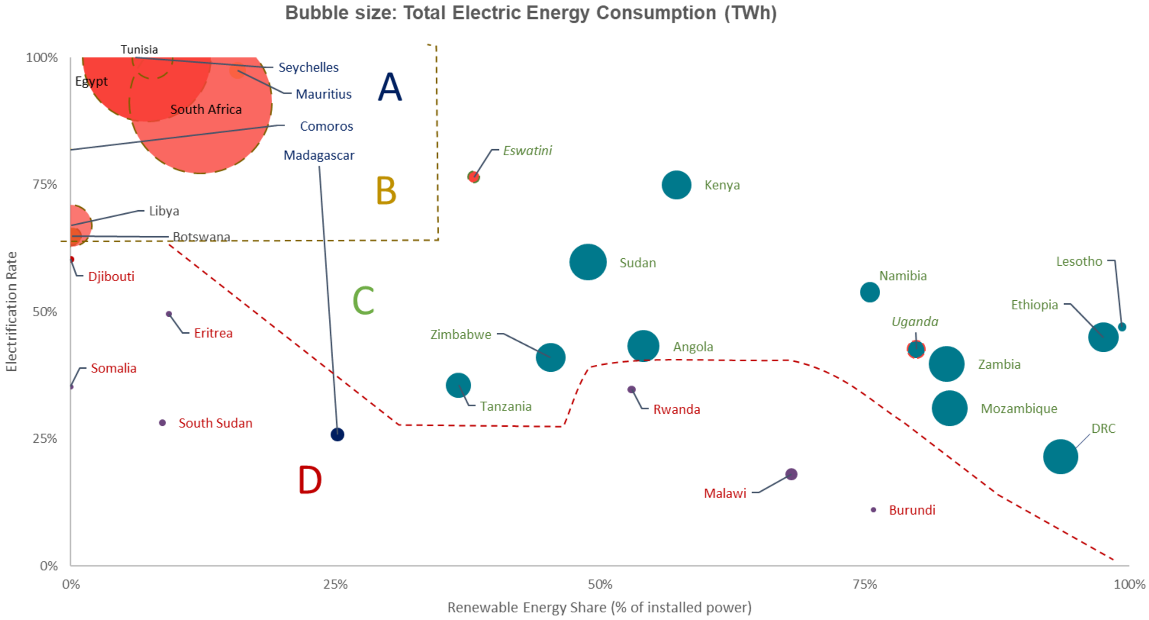
Based on these criteria, the following four generic power system categories are introduced in the table below. The categorisation indicators are not quantified and should be regarded as indicative rather than absolute.

Table 4-1: Sorting criteria for categorisation of power systems in the EA-IO-SA Region

Type	Interconnector opportunities?	Renewable Energy Share [%]	Electricity use per capita [kWh]	Electrification Rate [%]	Total electricity demand [TWh]
A: (Indian Ocean) Island States	No				Small
B: Fossil-based, high use of electricity	Yes	Low	High	High	Large
C: Partly renewable, intermediate use of electricity	Yes	Medium/high	Medium	Medium/high	Medium
D: Limited size, consumption, and renewable energy share	Yes	Low/medium	Low	Low	Small

As shown in Figure 2-14 on page 2-12, most non-island countries have existing, committed, or planned interconnectors. The number of existing interconnectors is therefore not used as a categorisation parameter. However, island states are put in a separate category as they have to be self-supplied with electricity and cannot rely on exchange with adjacent countries. Although focused only on the Indian Ocean island states, advice provided for type A countries may also be valid for countries which are yet to be connected to neighbouring countries. The bubble chart in Figure 4-1 places the countries in the EA-SA-IO-region into different categories based on the above criteria.

Figure 4-1 Categorisation of EA-SA-IO Power Systems



Sources: See Appendix A

Two countries are highlighted with colored borders, indicating they could have been placed in more than one category (See Appendix A for more details). Uganda has a high renewable energy share, and an electrification rate that in the mid-range of the countries categorised as countries with medium electricity intensity and intermediate to high renewable energy share. However, the country ranks in the bottom five in total electricity consumption per capita. The country could therefore be placed in both category C and D. Eswatini is a small power system, and with a fair portion of its electric energy supply from renewables, this correlates with category C. The high level of electric energy consumption per capita and the high electrification rate means that Eswatini also could be categorised as type B. Finally, Djibouti is a power system with a relatively high electricity use per capita. However, being entirely based on fossil fuels and having a small total system size, the system is indicatively placed in category D.

These are not the only countries where one or more attributes mean that they could be placed in several of the categories. The dividing line between category C and D is now drawn so that Tanzania and DRC fall into category C and Rwanda into category D, even though Rwanda has an electrification rate similar to Tanzania and a renewable energy share between the other two. This is based on an assessment of the system size and total electricity consumption per capita.

Readers are advised that the categorisation is merely an attempt to identify suitable guidelines for power systems with different characteristics, which may be relevant for all member states. As system characteristics change with time, utilities are encouraged to actively assess how, and to what degree the guidelines provided may be relevant for their specific system.

4.2 A: Indian Ocean Island States

The Indian Ocean Island States differ from the other countries in the EA-SA-IO region by being separate systems with no prospects for being interconnected to adjacent power systems. Though the countries differ in size and grid development, they are placed in a separate category because they will need to be self-reliant, and because interconnectors cannot be used to provide flexibility. In that sense, Category A guidelines are also highly relevant for mainland countries which are not yet connected to neighboring countries.

All the countries in category A are power systems with total electric energy demand below three TWh, yet they face different challenges. On the one hand, Madagascar has a large, geographically dispersed population with low electrification rate and may need to develop a power system based on distributed resources and rural mini-grids before establishing a larger, centralised grid. On the other hand, Seychelles and Mauritius, and partially also Comoros, have near universal access on small islands fed mainly by fossil-fuel based generators. The share of the population categorised as urban is intermediate, indicating that distribution grids play a vital role in the energy supply in the interconnected grid.

Key characteristics of category A power systems are that they have a supply side which is mainly based on small and medium sized fossil-fueled plants, including dispatchable load following thermal plants. The reach of the transmission grid is relatively limited, and system voltages are moderate. Power is distributed through a distribution grid to end users. Therefore, renewables have the potential to rapidly play a dominant role in these power systems. In order to accommodate a transition to renewable based power systems on the islands it is important that power system flexibility and controllability is maintained. As interconnectors are not a viable flexibility option, island states may benefit from more costly flexibility options such as energy storage or sector coupling to heating, hydrogen or other options often called "Power to X", or "P2X". Flexible end-users and prosumers may play an important part in facilitating a high share of renewables in the power system.

Issues that should be considered in category A systems include:

Table 4-2: Issues for consideration in category A systems

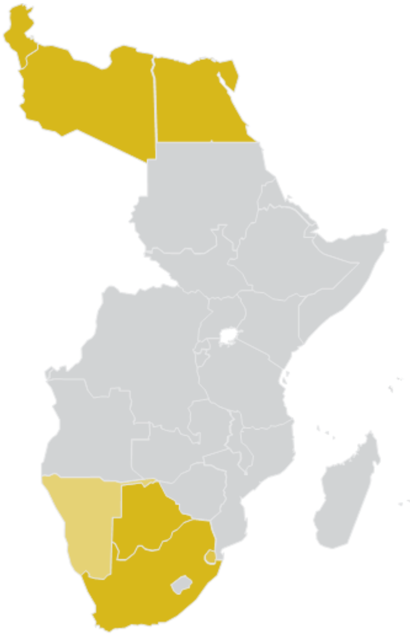
Supply side	**Adequacy** - Capacity margin & availability - Flexibility & dispatchability - Spinning reserves, ramp rates, inertia. - Retrofitting thermal units for lower min. load levels
Transmission	If HV transmission: **Security** - Congestions/bottlenecks **Resilience & Adequacy** - Redundancy ("N-1")
Distribution	**Security** Hosting Capacity **Adequacy** Coordination with micro grid and off-grid planning
Storage	Both distributed and utility scale may prove vital for flexibility and reduced reliance on diesel gensets Long term-storage may prove vital in a transition to high-RE-systems
Demand Side	**Flexibility** (Residential) Demand side response Prosumers

Grid codes and technical requirements should reflect the fact that systems are small. A common practice in handling VRE in grid codes and technical requirements is that small plants are not subject to the same technical requirements as larger installations. Given the limited size of their systems, however, small island states should consider carefully whether or not less stringent requirements should be allowed for smaller renewable plants such as, for instance, distributed rooftop solar PV.

Locations of renewable plants could focus on areas of the grid where grid capacity is already strained. In such locations, adding power production from renewables could in fact improve grid conditions, allowing for better use of the existing grid capacity.

4.3 B: Fossil-based, High Use of Electricity

Category B represents developed power systems, based on fossil fuels. In order to fall into category B, the power system should have an electrification rate above 50 percent, a renewable share below 25 percent, and an electric energy consumption per capita above 1,000 kWh.



Countries that fall within this category are South Africa and the North African countries Tunisia, Libya, and Egypt. The two countries that stand out from the rest are South Africa and Egypt. Total electric energy consumption in each of these countries is ten times the size of Libya, the country with the third largest energy consumption in the 2018 statistics. Though the total electric energy demand in the power systems in Botswana and Eswatini is small, the high electrification rate and high electricity use per capita mean they also could fall into category B. Namibia has a high domestic electricity use and electrification rate and could be a candidate for category B but has been placed in category C due to its high share of renewables in the supply mix.

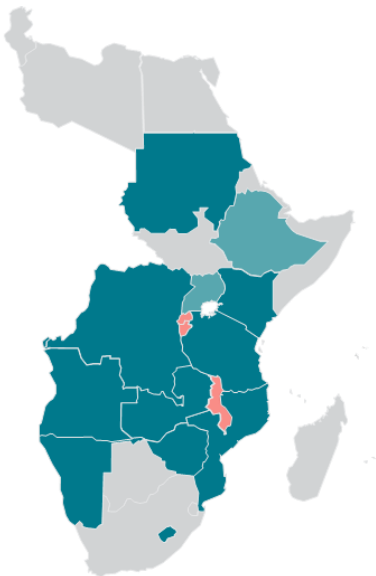
Variation between the category B countries consist of the size of the country (and reach of the grid), as well as the total system size.

A key characteristic of category B power systems is that they have a supply side which is based on large fossil-fueled generation plants. Power is transferred to load centers through a relatively well-developed transmission grid and distributed through a distribution grid to end-users. The countries have a moderate to high electricity demand from their industrial sectors, supplied at high voltage, and a relatively developed residential customer base including several large urban load centers. Issues that should be carefully considered in category B power systems are outlined in the below table.

Table 4-3: Issues for consideration in category B systems

Supply side	**Adequacy** - Capacity margin & availability - Flexibility & dispatchability - Operational reserves, ramp rates - Operational planning (unit commitment, start/stop)
Transmission	**Security** - Congestions/bottlenecks **Resilience & Adequacy** - Redundancy ("N-1") - Interconnector capacity
Distribution	**Security** Hosting Capacity
Storage	Short term storage may accommodate short term fluctuations in VRE output which may not be covered by slow operating thermal plants. Medium term storage could be an option due to slow start-up times for thermal plants
Demand Side	**Flexibility** Industry demand side response, Aggregated demand side response

4.4 C: Partly Renewables-based, Medium Sized Systems



Category C represents intermediately developed power systems where renewables already play a significant role in the energy mix. In order to fall into category C, the power system should have a renewable share above 25 percent and an electric energy consumption per capita above approximately 100 kWh. The total system size should be above one TWh. Electrification rates in category C should not be extremely low, without being specified further.

Countries that can fall within category C include Eswatini, Namibia, Lesotho, Angola, Sudan, Zimbabwe, Zambia, DRC, Kenya, Tanzania, Mozambique, Ethiopia, and Uganda. Ethiopia and Uganda have low electricity demand per capita that could point towards category D, but are included in C due to their high share of renewables. Malawi, Rwanda and Burundi also have large renewable energy shares but are put in category D due to the low electrification rate, small system size and low level of electricity use per capita.

Countries in category C have large shares of hydro power in their systems. This means that some of the hydro power plants may be designed as baseload plants, typically operating around a best efficiency point. Increased VRE penetration in the system will lead to more starting/stopping of units, and operation outside the best efficiency point. This means that more maintenance may be required on existing plants in order to cater for the increased wear and tear. Although maintenance requirements may increase, reservoir-based hydro power is well-suited to operate alongside variable renewables because it is controllable, has short start-up times and normally also high ramp rates. Hydro power production may be reduced or stopped when VRE production is high during the day and quickly ramp back up again at night.

Global climate change has introduced a risk of decreased water availability over the year. Several sources suggest that average precipitation in the region could decrease as a result of climate change (Spalding-Fecher, Joyce, & Winkler, 2017) . A high dependence on hydropower could therefore imply a risk of electricity supply disruption. Dry years will normally translate to higher generation output from solar PV power plants than wet years, and wind power generation also has a negative correlation with precipitation. Diversifying generation portfolios in hydro-dominated countries with VRE is therefore considered a viable option for mitigating the impact on electricity supply in dry years. Issues that should be carefully considered in category C power systems are outlined in the below table.

Table 4-4: Issues for consideration in category C systems

Supply side	**Adequacy** - Capacity margin & availability - Flexibility & dispatchability - Operational reserves Operational planning (unit commitment, start/stop)
Transmission	**Security** - Congestions/bottlenecks **Resilience & Adequacy** - Redundancy ("N-1") - Interconnector capacity
Distribution	**Security** Hosting capacity - thermal and voltage control **Adequacy** Coordination with micro grid and offgrid planning
Storage	Utilisation of hydro reservoirs Short term storage may accommodate short fluctuations in VRE output
Demand Side	**Flexibility** Industry and aggregated demand side response Strategic load growth

4.5 D: Limited System Size, Consumption, and Renewable Energy Share

Category D represents countries with small electric power systems (<5 TWh) and limited electric energy consumption per capita (<100 kWh). Another attribute of category D countries is the low electrification rate (<50 percent) as well as a relatively low share of renewables in the domestic power system.

Countries that fit into category D are Somalia, South Sudan, Eritrea, and Djibouti, as well as Malawi, Rwanda, Burundi and to a certain degree also Uganda and Ethiopia (low electricity use per capita, but high renewable energy share). The small power systems of Lesotho and Eswatini could also fit into category D due to the small size. However, their high electrification rate has lead them to be placed in other categories. DRC has a low electrification rate, but high share of renewables in the system and relatively large system size and is not highlighted in the figure to the right.

A key attribute of power systems placed in category D is that they are relatively small, meaning that VRE has the potential to play a key role even in the short run. Scheduling of plants in order to ensure sufficient reserve margins while avoiding too much curtailment will be important in order to facilitate increased development of low-cost VRE. Baseload renewables should be considered as options to replace fossil-based baseload plants, and interconnectors should be highly prioritised in order to provide flexibility.

The countries in category D vary by land area, population, and geographic reach of the grid. Where a national grid exists, renewable energy location should be considered carefully. The optimum site based on resource availability may not correlate well with where the demand is located or where the grid has sufficient capacity. Limited grid capacity may impact where new production should be placed. In countries with poorly developed transmission and distribution grids, grid expansion must go hand in hand with development of new generation facilities.

Centralised production must be followed by sufficient transmission capacity, and/or be located near new demand. Finally, small-scale distributed generation may need to face strict technical requirements in order to provide grid services such as for instance voltage control in order best to utilise existing grid capacity.

Issues that should be carefully considered in category D power systems include:

Table 4-5: Issues for consideration in category D systems

Supply side	**Adequacy** - Capacity margin & availability - Flexibility & dispatchability - Spinning reserves, ramp rates, inertia
Transmission	**Security** - Congestions/bottlenecks **Resilience & Adequacy** - Develop key transmission projects - Prioritise interconnector opportunities
Distribution	**Security** - Hosting capacity in existing distribution grid **Adequacy** - Distribution grid development planning. - Coordination with micro grid and offgrid planning
Storage	Consider for implementation of VRE and as alternative to grid reinforcements
Demand Side	**Flexibility** Strategic load growth

5 Harmonised Guidelines

Key chapter takeaway

- **New production should be subject to functional requirements.**
- **Grid flexibility and controllability becomes increasingly important as VRE deployment rates continue to rise and should be prioritized in grid planning.**
- **Distributed renewables such as rooftop solar PV mean grid capacity at the local and regional level becomes increasingly important. Utilities should have a proactive approach to ensuring sufficient local and regional grid capacity.**
- **Interconnectors and key in-country transmission corridors can play an important role in unlocking the full renewable energy potential in the EA-SA-IO region and should be pursued.**

Optimal resource utilisation in the power system is achieved when each individual component is allowed to do what it does best. Unlimited grid capacity would mean that the grid does not place restrictions on neither production nor demand. In practice, however, grid capacity is a limited and costly resource and increasing grid capacity is not always the optimum solution. In order to utilise the grid and facilitate increased production from renewables in the best possible way, all parts of the power system must play together.

On the *demand* side, customers can adapt as long as the supplied electricity is able to fulfill the tasks it is meant to fulfill. For instance, use of heat pumps and water heaters and charging of electric cars can be moved to times when the grid is not heavily loaded. New consumption can, to a certain extent, be connected where it is good for the network.

Power *production* can contribute with various attributes that can be useful for the power system. VRE is dependent on the availability of solar irradiation and wind in order to provide active power but can, if properly designed, contribute with voltage regulation. The unpredictability of VRE can be reduced with a focus on good forecasting. Thermal power plants can contribute with baseload as long as fuel is available. Hydropower can contribute with a high degree of dispatchability but may be prone to droughts.

The *transmission and distribution grid* must be built so that the power can be transported from where it is produced to where it is needed. Sufficient grid capacity prevents each area or country from having to overinvest in production capacity to cover its own consumption. Areas with good renewable energy resources can supply areas with high consumption.

Storage can be a good way to enable better utilisation of the existing production and grid. By providing services for system operation and for solar PV and wind generators, storage can defer investments in peak generation and grid reinforcements.

The power system of the future will have to be smarter and more adaptable. Access to, and processing of, *measurements and data* will be important in order to develop a flexible power system, which utilises all resources in the best possible way.

Policy makers, regulators and system operators are advised to apply a holistic approach to the increasingly integrated energy systems in order to unlock and utilise grid capacity to enable greater integration of low-cost VRE. Key elements in such an approach are presented in the following sections.

5.1 First Key Element: Apply Functional Requirements in Grid Codes

Although systems that resemble each other in key characteristics may be described and sorted into common categories, no power system is exactly similar to another. Regardless of their idiosyncrasies, the need to operate the interconnected electricity grid safely and securely is shared among countries and regions. By focusing on *functional requirements* instead of fixed technical specifications, utilities should be well-placed for a future where power systems become increasingly interconnected, increasingly complex, and increasingly renewable.

Basing the assessment of new connections on functional requirements ensures that system conditions are always met before allowing new generation to come online. The drawback is that this approach is based on often comprehensive studies and documentation prior to allowing new connections.

Renewables may come in the form of large geothermal, solar, wind, or hydro power, or as distributed small-scale hydro or rooftop solar PV. Requiring the same studies and documentation for the smallest systems as for larger plants with much higher system impact may hinder the development of small-scale, distributed renewables. Having separate requirements based on installed capacity is a good approach for facilitating renewable growth, particularly at a small and distributed scale. A good example is rooftop solar. It does not make sense to require the same amount of documentation from a rooftop solar installation in the kilowatt-range as on large hydropower plants which may have installed capacities in the thousands of megawatts.

The same applies for demand; an industrial customer with large and complex electric loads that may be connected to the transmission grid and have a large system impact should be subject to more extensive requirements than a small customer at low voltage distribution level.

Policy makers should:

- Outline the responsibility assigned to each party when developing and assessing new connections to the power grid.
- Provide a legislative framework that ensures operators and regulators modify market designs, connection codes and operational procedures in order to accommodate a high share of renewables without compromising system security.

Regulators and/or system operators should:

- Ensure grid (connection) codes, and inteconnection agreements are based on functional requirements.
- Review and modify operational procedures so that it allows a high share of VRE while still ensuring safe and secure system operation.
- Ensure requirements are updated according to the technological development and adopted to best fit the idiosyncrasies of the national power system.
- Cooperate with other utilities to ensure harmonised functional requirements are developed where applicable.

5.2 Second Key Element: Coordinate Planning Efforts

Even though the previous paragraph made the case for placing less extensive requirements on connections with low system impact than large connections with greater system impact, this does not imply that utilities should apply a reactive approach to setting requirements for distributed energy resources. Grid hosting capacity assessments are an example of a proactive approach that allows utilities to assess the penetration of distributed energy solutions at which one needs to start performing more detailed studies to avoid costly surprises in having to upgrade large portions of local and regional grids.

Monitoring and reporting the existing and planned distributed generation at distribution level will also be important for system operators in their planning and forecasting work at the transmission system level. At the system-wide level, there is still the need for traditional grid capacity assessments, both specific interconnection studies for new plants and larger system studies in order to assure long term grid adequacy and the security of the grid. However, such studies and planning efforts need to address the reduced predictability introduced by variable renewables. This means that long term planning and the assessment of short-term fluctuations traditionally assigned to operational planning are bound to become more integrated.

International efforts should be part of the coordinated grid planning in order to assess the optimum development at regional level. Further development towards a fully interconnected regional power system with sufficient cross-border and in-country grid capacity can play a vital role in enabling more VRE to be integrated across the EA-SA-IO region.

Not only within the power sector should planning efforts be coordinated. The International Energy Agency (IEA, May 2019) highlights the importance of coordinating and integrating planning exercises across power market segments and even economic sectors such as transportation and industry. Any asset that uses power should be considered a power system asset and should be considered in an integrated energy system assessment. Making decisions in isolation may lead to foregone opportunities and sub-optimal development.

Policy makers should:

- Clearly define the role of system operators at national and local level (TSOs and DSOs)
- Create a framework which describes the rights and responsibilites of stakeholders regarding information exchange
- Ensure participation in transnational cooperation platforms

Regulators and/or system operators should:

- Create structures for cooperation and information sharing among various stakeholders
- Focus on the increased integration of planning and operational efforts
- Apply an active planning approach
    - Power system master plans, integrated resource plans and/or grid development plans should be produced at regular intervals.
    - Local development plans should be an integral part of the national grid planning
- Actively participate in regional forums for international cooperation among operators and regulators

5.3 Third Key Element: Enable Flexibility in All Parts of the System

Flexibility becomes increasingly important as VRE penetration increases. Regulatory frameworks, market design and incentivising schemes should be designed to reward flexibility in all parts of the power system – be it demand (distributed energy resources), storage, transmission and distribution, or supply side.

Conventional power plants are currently the predominant source of system flexibility in modern power systems. However, several countries have adopted market reforms and regulations to gain flexibility services from VRE plants. Examples include changes to connection codes which require VRE to contribute short-term flexibility services (e.g. primary frequency response) (IEA, May 2019).

The demand side is shifting from passive loads to distributed energy resources with a number of smart solutions for controllability of loads, more electric vehicles, and prosumers that produce power locally as well as consume it. The aggregated flexibility in these distributed energy resources can prove important at the system level. End users should therefore be incentivised to pick solutions that benefit the power system at large.

On the storage side, batteries are typical examples of components that can provide a multitude of system flexibility services simultaneously.

Grid flexibility can be provided through technological advances such as dynamic line rating or virtual power lines, or by reinforcing grid capacity. A sufficiently strong grid enables other flexibility resources to be shared among regions. For the mainland countries in the EA-SA-IO region, additional interconnectors which may provide systems operators access to a wider pool of demand and supply options will be an important grid flexibility resource.

Policy makers should:

- Ensure periodical mandatory review of system flexibility policies (including connection codes) in order to match the pace of technological development, and ensure that flexibility measures are considered as alternatives to traditional grid development
- Support research and development efforts, pilot projects, and demonstration projects to promote flexibility in their power system and the region at large
- Define clear rules for where ownership and operation of storage systems should be placed.
- Provide incentives to reduce upfront costs for storage and attract investments
- Support efforts that enable all resources to participate in flexibility schemes, including small-scale distributed energy resources

Regulators and system operators should:

- Provide a well-defined regulatory framework for ownership and operation of storage systems
- Develop a market design which awards flexibility services and promotes investments.
- Always consider flexibility as part of power system planning as an alternative to investing in grid or generation capacity.
- Gain experience by applying flexibility solutions through pilots and proof-of-concept projects

5.4 Fourth Key Element: Digitalise and Develop Data-driven Power Sector Decisions

The future is not only electric – it is also digital. Modern power systems already include a large amount of data production and collection. Information and communication technology solutions enable the continuous monitoring and gathering of a multitude of power system attributes. Information may include load and production data, surveillance videos, tests and samples of equipment, power flow and temperature measurements on transmission lines, system voltages, and meteorological data.

These technologies can enable more dynamic, efficient, reliable, and sustainable electricity systems, as highlighted by IEA through their 3DEN initiative[7]. Digitalisation offers significant benefits and is becoming an important tool and a crucial prerequisite for maintaining security of supply, ensuring flexibility, and enabling cost-effective solutions of the future energy system.

As power systems become more developed, more decentralised, and more digitalised, an increase in data gathering and the active utilisation of the data may allow technical personnel to make better decisions in planning and operation, thus utilising existing grid capacity in a more efficient way. For instance:

- Predictive maintenance and fault detection based on data analytics from advanced metering infrastructure can improve the security of the power system.
- Collection and utilisation of production and consumption data, coupled with data based renewable energy forecasting may allow operators to improve dispatch and scheduling activities.
- Line temperature measurements combined with historical power flow and measurements of ambient conditions can help define and predict more precise transmission line capacities.

Further, algorithms and artificial intelligence solutions may help optimise and automate efforts in order to further benefit from the large amount of data that may be collected from the power system. To develop appropriate solutions, utilities may need to work with technology partners who are not traditionally part of the power sector, but who have expertise with sensors, actuators, artificial intelligence, and data management.

Policy makers should:

- Develop long-term digitalisation policies which include the power sector
- Facilitate the development of common digital platforms and programs across sectors
- Support reseach and development efforts

Regulators and system operators should:

- Provide standards for the implementation and use of digital platforms in the power sector
- Assess and implement necessary hardware and software systems
- Continuously review and monitor requirements for data monitoring equipment and ICT solutions for new connections
- Pursue closer cooperation and joint efforts with the ICT sector, as well as the artificial inteligence and data analytics sector

[7] The IEA has launched a four-year cross-agency initiative, Digital Demand-Driven Electricity Networks (3DEN). 3DEN is working to accelerate progress on power system modernisation and effective utilisation of distributed energy resources through policy, regulation, technology and investment guidance. https://www.iea.org/areas-of-work/promoting-digital-demand-driven-electricity-networks

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Appendix A Data used in categorisation of countries

The table below lists data used as background for the selection of countries into the categories suggested. Data are valid for 2018, as this is the most recent complete data set. Data are gathered from the World Bank Global Electrification Database (World Bank, 2021), and United Nations Statistics Division (data.un.org). Details about the background of the UN data are described in (United Nations Statistics Division - Energy Statistics Section, February 2021).

Country	Electrification rate	Electricity use per capita [kWh]	RE%	Population ('1000)	Total electric energy consumption [TWh]
Madagascar	26 %	69	25 %	27691	1,92
Mauritius	99 %	2083	16 %	1272	2,65
Seychelles	100 %	4854	6 %	98	0,476
Comoros	82 %	68	0 %	870	0,0593
Libya	67 %	2562	0 %	6871	17,6
South Africa	85 %	3464	12 %	59309	205,4
Egypt	100 %	1618	7 %	102334	165,6
Tunisia	100 %	1396	8 %	11819	16,50
Botswana	68 %	1364	0 %	2352	3,21
Eswatini	74 %	1141	*38 %*	*1160*	*1,32*
Namibia	54 %	1641	76 %	*2541*	*4,17*
Lesotho	47 %	377	99 %	*2142*	*0,807*
Angola	45 %	308	54 %	*32866*	*10,1*
Sudan	52 %	312	49 %	*43849*	*13,7*
Zimbabwe	41 %	572	45 %	*14863*	*8,51*
Zambia	40 %	702	83 %	*18384*	*12,9*
DRC	19 %	111	95 %	*89561*	*9,97*
Kenya	61 %	162	57 %	*53771*	*8,70*
Tanzania	35 %	107	37 %	*59734*	*6,37*
Mozambique	31 %	407	83 %	*31255*	*12,7*
Ethiopia	45 %	*79*	*98 %*	*114964*	*9,09*
Rwanda	35 %	52	53 %	*12952*	*0,668*
Uganda	43 %	67	80 %	*45741*	*3,07*
Somalia	34 %	22	0 %	*15893*	*0,35*
South Sudan	6 %	40	9 %	*11194*	*0,446*
Eritrea	49 %	114	9 %	*3546*	*0,404*
Malawi	18 %	79	68 %	*19129*	*1,51*
Djibouti	61 %	475	0 %	*988*	*0,469*
Burundi	11 %	23	76 %	*11891*	*0,276*
Data source	*World Bank*	*UN*	*UN*	*UN*	*UN*

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