Smart Grids for Improved Grid Performance in Developing Countries

Focusing on the Region of West Africa

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DATE: 02/MAY/2017

Table of Contents

TABLE OF FIGURES

TABLE OF TABLES

LIST OF ACRONYMS

Table 0:1: List of Acronyms used in this report

ACRONYM	DEFINITION
AMI	Advanced Metering Infrastructure
DAS	Distribution Automation System
DSM	Demand Side Management
ECREEE	ECOWAS Regional Centre for Renewable Energy and Energy Efficiency
EnDev	Energising Development Program
ECOWAS	Economic Community of West African States
FACTS	Flexible Alternating Current Transmission System
HV	High Voltage
HVDC	High Voltage Direct Current
ICC	Information and Control Centre
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
O&M	Operation and Maintenance
PSS	Power System Stabilisers
SCADA	Supervisory Control and Data Acquisition
T&D	Transmission and Distribution
UFSL	Under Frequency Load Shedding
UVLS	Under Voltage Load Shedding
WAPP	West African Power Pool

ACKNOWLEDGMENTS

I would like to thank my supervisor, Peter Connor, for his support and advice during this academic year, guiding me through this project. I would also like to express my gratitude to all the people who took their time to speak to me about smart grids in developing countries and who were willing to share their knowledge with me. Without their help this report would not have been possible.

I would also like to thank my friends for their encouragements and for providing me with constant motivation. Finally, a special word of thanks goes to my parents.

ABSTRACT

This report investigates the potential for smart grid technologies to achieve improved grid performance in the region of West Africa. Grid performance is assessed based on the electricity networks losses, power outages and capacity for integrating new renewable energy generation, as well as the grid's ability to cover the electricity demands of the population. The results presented are based on an extensive literature review of smart grid technologies in developing countries, as well as a few expert interviews which were conducted to gain further insight into the opinions of some of the stakeholders currently involved in the sector.

The literature review on the general potential for smart grids in developing countries indicates that there are many opportunities for smart grid technologies to address some of the main problems experienced in electrical networks across many developing countries. However, the review also highlights the importance of detailed planning before implementing smart grid projects in developing countries, to ensure that limited financial resources are allocated effectively. Smart grid technologies need to be tailored to the specific needs of each individual country.

The evaluation of the potential for smart grids in the region of West Africa shows that there are numerous possible application points for smart grid technologies through the grid, including the transmission and distribution network as well as the consumer side of the grid. Furthermore, smart grid technologies can be integrated into mini-grid systems. The main potential improvement as a result of the implementation of smart grid technologies include a reduction in technical and non-technical losses (power theft and fraud) throughout the network, improved system stability, facilitated integration of renewable energy generation and more sophisticated revenue collection systems. The latter especially applies to mini-grids. These improvements could potentially lead to more secure and wide spread energy access.

1 INTRODUCTION

Smart grids have been a topic of much interest recently. They offer many advantages in terms of optimising the performance of electricity networks especially for more complex and decentralised networks. Most research on smart grids so far has been centred around their application in developed countries with sophisticated power infrastructure. This report will instead be investigating the potential for the deployment of smart grid technologies in developing countries, with a specific focus on the region of West Africa, where network infrastructure is less advanced. The report is broken down into six main sections. Section one consists of this introduction and section two outlines the methodology followed to obtain the results presented in this report. Section three sets up the framework for all further sections by defining some key parameters and important terms used through this document. This includes an outline of the electrification situation in West Africa presenting some of the main problems which the power grid in the region is currently facing as well as considering some of the targets which the region has set itself to overcome these problems. Furthermore, the main barriers which currently persist in the West African energy sector towards achieving these targets are examined. Section four then moves on to present an overview of smart grids in developing economies. This is done by investigating the caopportunities and barriers for smart grid deployment in developing countries as well as looking into the main drivers for smart grid investment. Section five examines the smart grid potential specifically for the West African electricity network. This section in further broken down into four sub-section according to the different areas of the grid in which smart grid technologies can be implemented: transmission networks, distribution networks, consumer side as well as mini-grids. Finally, section six concludes this document, drawing together the important points presented and offering some recommendations for the further development of the West African grid network.

2 METHODOLOGY

The work presented in this report is based mainly on an extensive literature review, with the addition of a few expert interviews and personal correspondences. The literature review is used to lay out the framework for this report, presenting background information and setting up definitions for important terms used within this report. Building upon this the report will present an overview of the currently literature available on the topic of smart grids for improved grid performance in the region of West Africa. A large range of reports, articles, and case studies are consulted, allowing for a comparison of their outlooks on the topic. The interest in smart grids for developing countries has increased significantly in the past few years, resulting in many recent studies published on the topic. However, the number of studies concentrating specifically on smart grids for the region of West Africa remains limited, making this one of the main drawbacks of the literature review. It should be kept in mind that a few more studies on this topic are most likely available in French language, as many of the West African countries are Francophone. However, for the most part these studies have not been considered in this report.

The interviews conducted are used to supplement the information gathered in the literature review stage and provide some insight into the views of various experts working in the sector. The interviewees where selected based on their expertise with smart grids in developing countries, their current or past employment positions working for various stakeholders involved in the sector, as well as based on their availability for meeting and conducting an interview. An attempt was made to consult experts from a variety of backgrounds, to gain insights into the views of different stakeholders. The interviews were conducted in a relatively informal and unstructured way, leaving the experts the freedom to express their own thoughts and ideas on the topic of smart grids in developing countries.

Table 2:1 provides an overview of the backgrounds of the experts interviewed. The main limitation of the interview stage is the small number of experts included, as well as the fact that several key stakeholders, such as local governments, grid operators, regulators and utilities, or electricity consumers and local communities are not represented.

Table 2:1: Overview of experts interviewed as part of this study

Organisation	Sector	Expertise	Reference
SolaPak	Private	Distributed solar PV and DC mini-grids	(SolaPak, 2016)
ECREE-GIZ Cooperation	Regional Organisation	Policy and economic advisor	(ECREE Advisor, 2017)
EnDev	International Donor Organisation	Mini-grid design, installation, and management in West Africa	(EnDev Mini-Grid Expert, 2017)
Formerly at EnDev	International Donor Organisation	Energy access in West Africa	(EnDev Employee, 2017)

3 BACKGROUND

This report will focus on the region of West Africa; more specifically on the countries which are part of the West African Power Pool (WAPP). The WAPP is a specialised organisation formed in 1999 by the Economic Community of West African States (ECOWAS). Fourteen of the fifteen ECOWAS states shows in Figure 3:1 are part of the WAPP. This includes the countries of Benin, Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo. The only ECOWAS country not part of the WAPP is Cabo Verde. As an island state Cabo Verde is isolated from the continental grid and face slightly different energy challenges in comparison to the other ECOWAS countries. The vision of the WAPP is "*to integrate the operations of the national power systems into a unified regional electricity market, which will, over the medium to long term, assure the citizens of ECOWAS Member States a stable and reliable electricity supply at competitive cost."* (WAPP, 2011e) The WAPP aims to do this by developing closer regulatory integration in the region, as well as increasing the trading volume between its member states, which currently still very low. Unlike the other African power pools the WAPP is directly responsible for developing new infrastructure to facilitate this (Smart Villages, 2015).

Figure 3:1: ECOWAS Member States (UNECA, 2016)

3.1 ELECTRIFICATION IN WEST AFRICA

Electricity access rates in the region of West Africa are amongst the lowest in the world (Smart Villages, 2015). In 2014 only around 34% of the population of WAPP countries had access to electricity. In rural regions access levels are even lower, at only around 17%. The energy access rates vary somewhat between the different West African states as illustrated in Figure 3:2 (IEA, 2016). Even in areas with electricity access, the capacity of electricity which is available is often limited (Yeboah, 2014). In between the years of 2006 and 2010 it was estimated that the suppressed demand in West Africa was around 7 to 10 TWh. (ECOWAS, 2015b) West Africa currently has the world's fastest growing population (CILSS, 2016). Furthermore, the region is becoming increasingly more urbanised (Escudero, et al., 2017). As a result, the demand for electricity in West Africa expected to increase significantly in the future (Miketa & Merven, 2013).

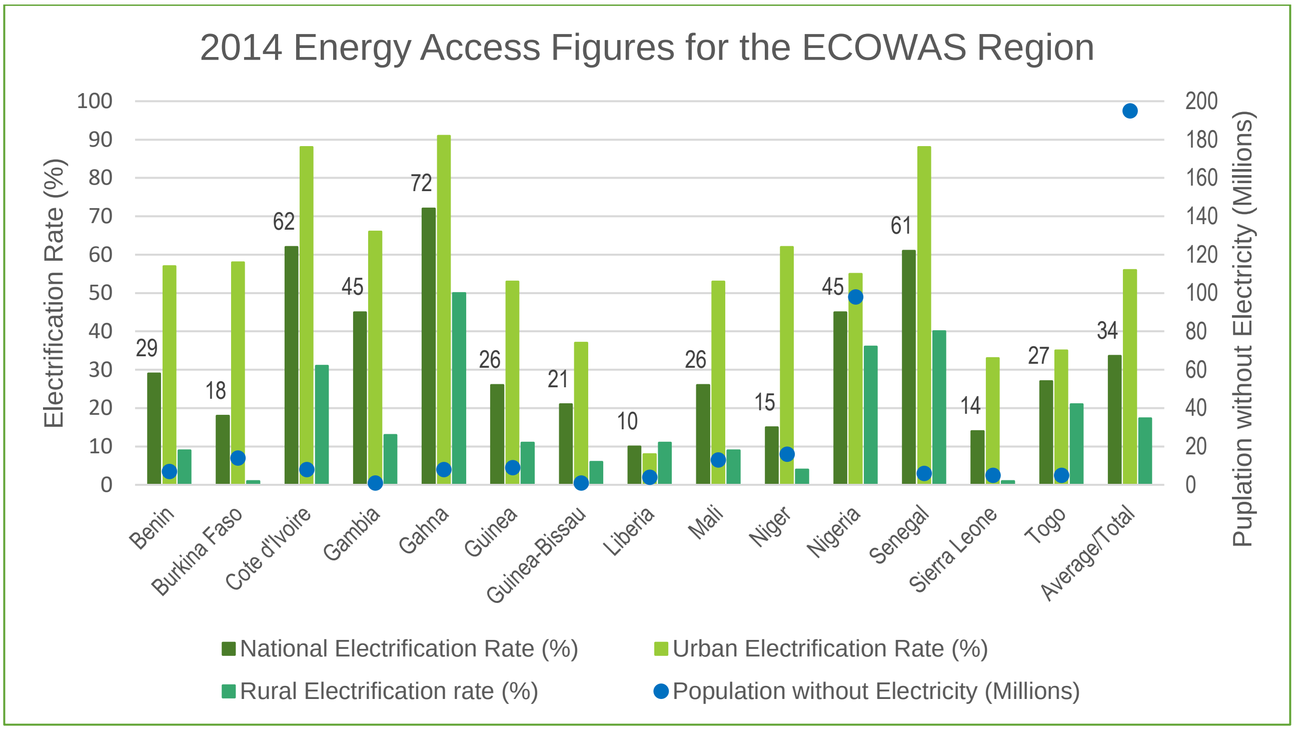

Figure 3:2: Access to Electricity in the ECOWAS Region (IEA, 2016)

3.1.1 Current Energy Problems

Several obstacles lie in the way of achieving 100% access to electricity in West Africa. The electrical system is challenged with an increasing gap between the predicted demand, existing supply capacities and limited availability of capital investment. The problem is further increased by the high electricity losses which occur in the system during generation, transmission and distribution (ECOWAS, 2015a). In addition to this, power theft and other illegal operations result in further losses of up to 30% (Yeboah, 2014). Overall, losses in the region's electricity grid vary from 15 to 40% (or 20 to 60% per Kotura, 2016), which is extremely high in comparison to the normal losses of around 7% in more developed grids (ECOWAS, 2015a). Figure 3:3 illustrates these losses.

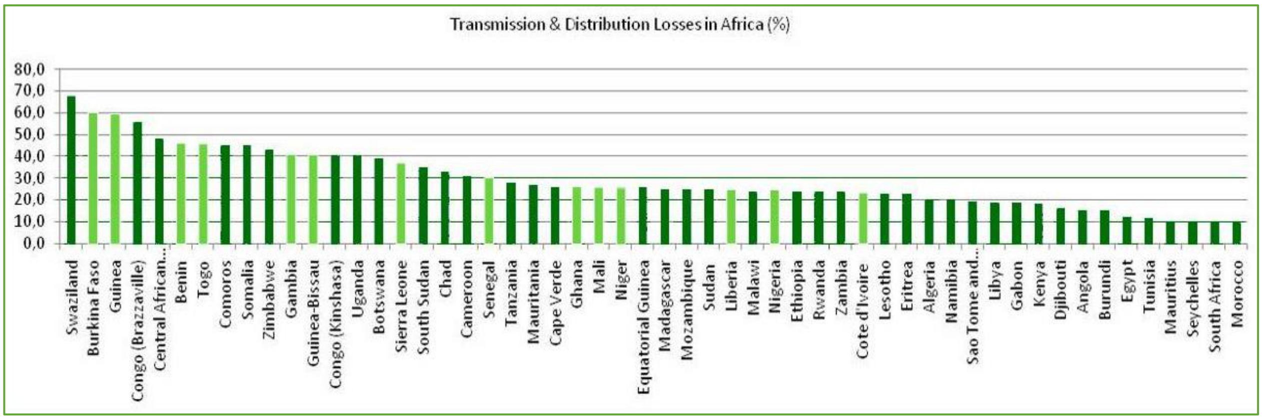

Figure 3:3: Transmission and distribution losses in Africa in 2014. West African countries are highlighted (Kotua, 2016)

A further issue is the large dependency of many West African countries on imported fuels such as diesel and oil for power generation, which can account for up to 90% of electricity generated. Fuel shortages and fluctuations in the international oil price threaten the energy security of the region and result in high generation costs (ECOWAS, 2015b). Regular power shortage results in blackouts and load shedding, which has adverse effects on the social and economic development of the countries (ECOWAS, 2015b).

High grid connection costs represent a further obstacle for large parts of the population in terms of gaining energy access. These high connection cost are a result of the great expenses involved when expanding the transmission network to reach the large share of scattered rural population. However, even in urban areas, where a network is already present, the connection coast is often too high for poor families (ECOWAS, 2015a).

Operation and maintenance issues add yet another burden to the stability of the power network in West Africa. Lack of upkeep often results in failures in the network and reduced availability of capacity.

Due to the compilation of these issues and inefficiencies in the power network, consumer tariffs are often very high and even then, they are often not able to recover the full costs involved. In many cases tariffs are subsidised by the government to make them affordable (ECOWAS, 2015b). The average tariff in the WAPP member states is around US$0.10, which is much higher than electricity tariffs in many other African countries (WAPP, 2011d).

3.1.2 ECOWAS Energy Targets

To overcome these problems, the ECOWAS region has set itself targets, both in terms of increasing renewable energy capacity as well as improving the energy efficiency of the grid network. These targets include:

- Increasing the share of renewable energy in the region's overall electricity mix to 10% in 2020 and 19% in 2030. (35% in 2020 and 48% in 2030 when including hydro).
- Expanding mini-grids and stand-alone systems to providing electricity access to 25% of the population by 2030.
- Reduce average losses in electricity distribution from the current levels of 15 - 40% to the world standard levels of below 10%, by 2020.
- Implement efficiency measures that free-up 2000 MW of power generation capacity by 2020. (ECOWAS, 2015a; ECOWAS 2015 b)

The region of West Africa has a high renewable energy resource potential, which should allow it to reach these targets. The main resources available include solar power, especially in northern countries, wind power in coastal regions, as well a micro-hydro and biomass (Smart Villages, 2015). For more details on renewable energy resources available see Appendix B).

Smart grid technology has the potential to assist the ECOWAS region in achieving their renewable energy and energy efficiency targets, especially in terms of reducing the losses in the system and increasing the share of renewable energy generation, as well as for the expansion of mini-grids for rural electrification.

Figure 3:4 outlines the ECOWAS plan for expanding the future electricity supply, using a mix of on and off-grid solutions. Figure 3:5 shows the current and future energy mix of the region, as predicted by IRENA based on the renewables promotion scenario outlined in ECOWAS and WAPP planes.

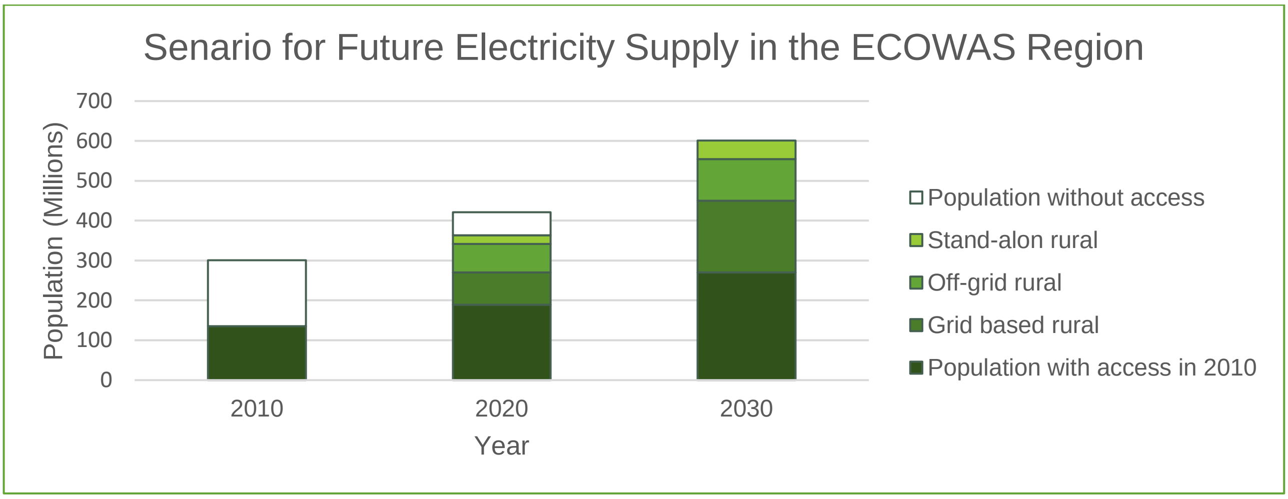

Figure 3:4: Scenario for future electricity supply in the ECOWAS region (ECOWAS, 2015b)

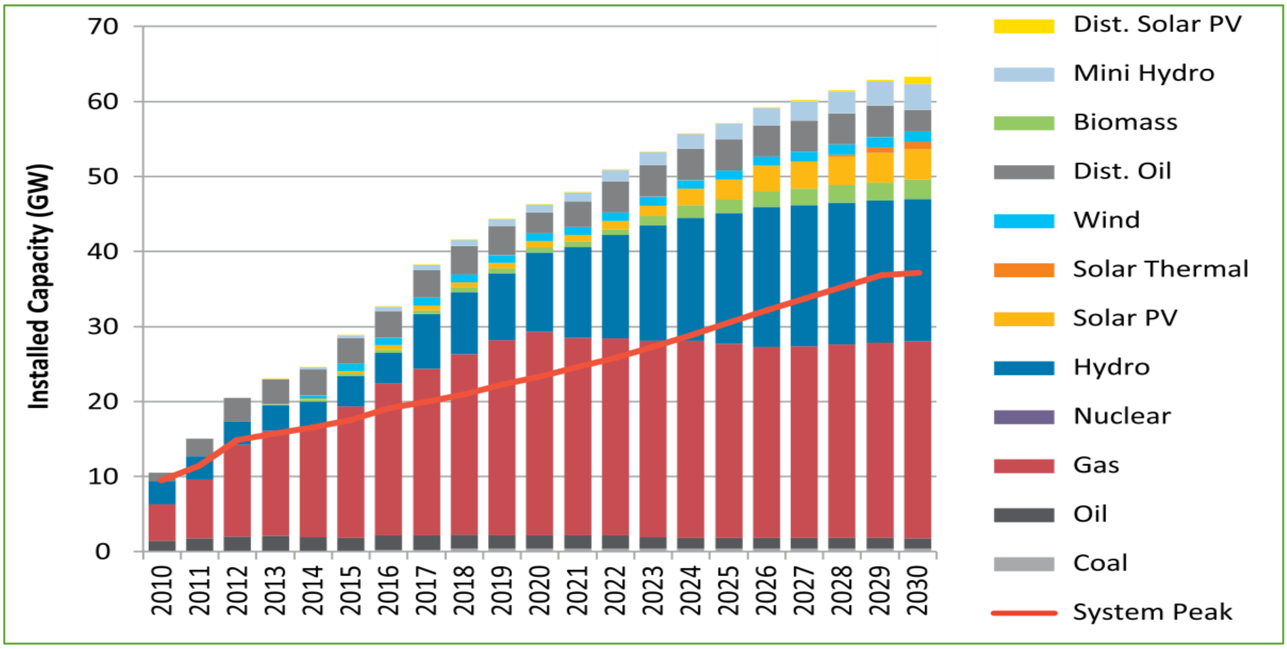

Figure 3:5: Capacity Balance under the Renewable Promotion Scenario (Miketa & Merven, 2013)

3.1.3 Main Barriers to Achieving the ECOWAS Energy Targets

The current **policy and regulatory environment** for renewable energy and energy efficiency, in the ECOWAS area, is not very developed. The policies of most West African states favour traditional, centralised energy generation. Grid development projects are often subsidised, which discourages investments for off-grid solutions such as renewable mini-grids (ECOWAS, 2015b). Overall the policy and regulatory framework for renewable energy and energy efficiency in most West African countries is weak (Smart Villages, 2015). Even in those countries which have set up specific policies, the legislation is often not strong enough to properly enforce them. However, there is a growing realisation of the importance of the topic and an increasing acceptance that action in this field is required (ECOWAS, 2015b).

As a result of the lack of clear and defined regulations, renewable energy and energy efficiency projects struggle to secure **financial resources**, which hampers the progress of these industries. This is especially the case for renewable energy technologies, where the upfront costs tend to be very high and the lack of adequate financing mechanisms proves to be a real barrier. Renewable energy technologies are often perceived as too expensive and unreliable and therefore unattractive for investors. In addition, electricity prices in many West African countries are subsidised by the government, which further lengthens the payback time for renewable energy investments (ECOWAS, 2015b).

Currently the renewable energy **market lacks in critical mass**, thus not offering promising conditions for local businesses. Therefore, procuring the necessary equipment as well as finding technically trained local professionals for maintenance works on renewable energy and energy efficiency projects is often very challenging. In addition, there is a **lack of standards and quality control**, both for locally manufactured and imported products. This results in poor quality products infiltrating the market, which can ruin the consumer's confidence in the technology. Since public **awareness** of renewable energy technologies is quite low already this can have very adverse effects for the industry (ECOWAS, 2015b). Especially the value of energy efficiency measures is often not appreciated. This lack of awareness makes it very difficult to achieve energy efficiency improvements through a change in consumer behaviour (ECOWAS, 2015a).

In general, there is a **lack of capacity** in the renewable energy and energy efficiency sector. There is a need for trained technical personal, R&D, pilot and demonstration projects as well as a strengthening of national institutions for the implementation of renewable energy and energy efficiency projects. (ECOWAS, 2015a) Furthermore, the coordination between the different West African stakeholders in the renewable energy and energy efficiency sector needs to be improved. (ECREE Advisor, 2017). A further barrier is the **lack of data available** for conducting resource assessment, which presents an obstacle for potential investors. (ECOWAS, 2015b).

3.2 Definition of Terms

3.2.1 Smart Grid

Various, slightly altering, definitions have been proposed for the term smart grid. In this report the term **smart grid** will be used in line with the definition proposed by the IEA in their report *Technology Roadmap: Smart Grids*, which states that a *"smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience and stability."* (IEA, 2011) Smart grids usually encompass the full electricity system, including transmission and distribution networks, the generators, grid storage systems and end-users. Figure 3:6 shows the different areas of application for different smart grid technologies through the network (IEA, 2011).

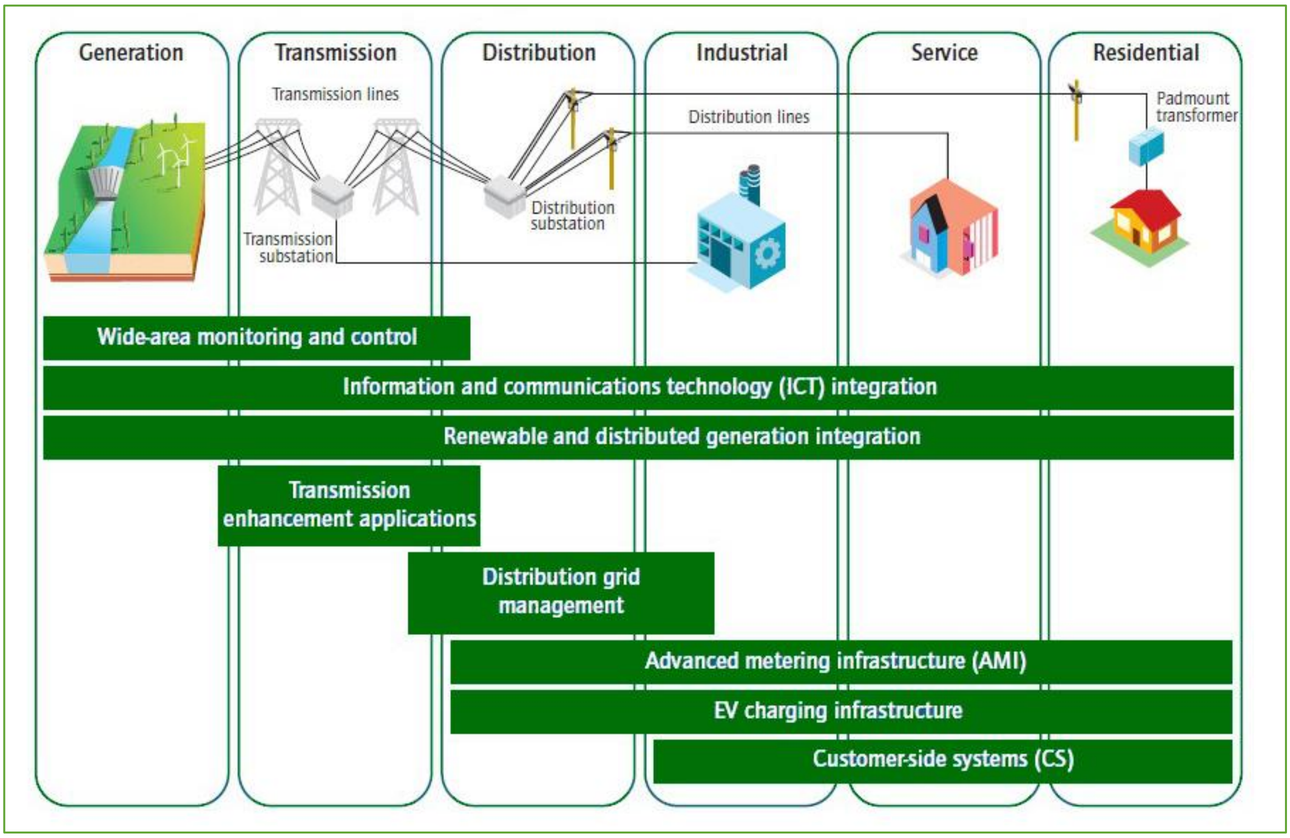

Figure 3:6: Smart grid technology areas (IEA, 2011)

Smart grids can vary significantly in terms of their design and layout. The one critical component which sets a smart grid apart from the usual grid is that it includes some form of communication network in addition to the traditional power network. The number of different smart grid technology and appliances available is rapidly increasing. Some of the most commonly implemented smart grid technologies include:

- Advanced Metering Infrastructure (AMI), including smart meters, in home displays, servers, relay, communications equipment to improve revenue collection, combat electricity theft, receive outage notification as well as service and maintenance scheduling.
- Advanced electricity pricing, often including more complex tariff structures to influence consumer behaviour.
- Demand response, using AMI to target the consumer’s control over systems and devices, thus being able to shift peak loads, increase the system flexibility and make use of cheap time of use tariffs.
- Distributed automation which uses automated re-closers, switches, capacitors, remote-controlled distributed generation and storage, transformer sensors, as well as wire and cable sensors to allow for an automated control of the cgrid during various scenarios.
- Renewable resource forecasting, whereby weather forecasting is used to predict the future availability of renewable power on the network.
- Smart inverters which are digital inverters with a programming interface capable of sending and receiving information. They can be used to quickly identify O&M issues as well as to remotely controlling the inverter.
- Distributed energy resources, including power conditioning equipment and communications and control hardware for grid/off-grid power generation technology.
- Distributed storage including power conditioning equipment and communications and control hardware for storage technology or power conversion technologies.
- Transmission enhancement, using superconductors, Flexible Alternating Current Transmission System (FACTS) and High Voltage Direct Current (HVDC) to improve network stability and automated recovery.
- Mini/Microgrids, which are defined in 3.2.2 below. (Kempener, et al., 2015), (IEA, 2015b) (IEA, 2011) (Zipp, 2014)

3.2.2 Local Grids

Local grid is a broad term used to describe grid systems which operate separately from the national utility grid. Various, sometimes conflicting, definitions have been composed to describe different types of local grid systems (Nordman, 2016). The term **mini-grid** is often used to describe a network which involves "*small-scale electricity generation (from 10kW to 10MW), and the distribution of electricity to a limited number of customers via a distribution grid that can operate in isolation from national electricity transmission networks and supply relatively concentrated settlements with electricity at grid quality level."* (Franz, et al., 2014) In the energy access sector the term **micro-grid** describes a system similar to a mini-grid, but operating at a smaller size and generation capacity (1-10 kW) (Franz, et al., 2014). However, outside of the energy access sector the term micro-grid is sometimes used to referred to a network which contains loads and distributed energy resources and which **can connect and disconnect from the main utility grid** (Nordman, 2016)**.** In this report the terms mini and micro-grids will be used based on the definitions from the *Mini-grid Policy Toolkit*, written by Franz, et al, (2014) as they are most relevant to the applications in developing countries.

For many developing countries, off-grid energy systems, such as mini-grids, present the most economical and solution for providing energy access to the population, especially in rural areas (Kempener, et al., 2015). Therefore, when investigating the potential of smart grids in developing countries it is essential to also consider the role of local grids. Mini-grids can be designed to incorporate a communications network, which turns them into 'smart mini-grids', based on the definition of a smart grid outlined in section 3.2.1.

3.2.3 Grid Performance

Many different criteria and benchmarks have been developed for assessing various grid performance parameters (Wu & Sun , 2008). However, in this report grid performance will be assessed simply based on 1) network losses 2) power outages 3) population served 4) consumer tariffs and 5) integration of new (renewable) generation capacity, since these are the main aspects of concern for grid development in West Africa (ECOWAS, 2015b).

4 Smart Grids in Developing Economies: An Overview

The large interest in smart grids is relatively new, and most of the research and investment on the topic has come from developed countries, mainly in Europe and North America. Smart grid development is currently still tied very closely to the economic development of countries. Furthermore, most smart grid development so far has been focused in countries with high renewable energy targets, as they are starting to face problems with the stability of their power supply due to more intermittent generation. For most developing countries, renewable energy generation is not a top priority, as they are more concerned with achieving universal energy access (Álvarez, et al., 2014). Nevertheless, the potential for applying smart grid technology in developing countries is increasingly being explored (IEA, 2011). Most case studies published on the topic of smart grids in developing countries so far focused on more emerging economies, such as China, India, Brazil, and Mexico. As of yet, very little experience has been gathered with smart grid technology in the world's least economically developed nations.

However, smart grid technology presents many advantages for improving grid performance and increasing energy access in these less developed economies. Most developing countries still have largely underdeveloped grid networks, giving them the opportunity of leapfrogging in terms of technical development and going straight for a smart grid network when expending their infrastructure. Especially if the country is planning on expending its renewable energy capacity, investing in smart grid technology will be advantageous, due to the increased flexibility and grid responsiveness gained (IEA, 2015b).

Nevertheless, smart grid projects in developing economies should be assessed and evaluated carefully, especially on a financial level, to ensure that the limited amount of capital available in these countries is invested wisely. Recovering the costs for smart grid investment might prove to be difficult in developing countries, due to the cap on the amount by which utility tariffs can be raised and still remain affordable for the majority of the population. It should, however, be considered that smart grid technology is often mutually reinforcing, so that while initial investments may be quite high, future projects can easily build upon existing technology, thus reducing their payback time. Table 4:1 summarises some of the opportunities and challenges which smart grids present for developing countries (Kempener, et al., 2015).

When implemented effectively, and combined with increased renewable energy capacity, smart grids can bring along many benefits for developing countries, especially in terms of reducing power outages and electrical losses in the system. Table 4:2 lists the main benefits, as determined by an IRENA study on smart grid in developing countries. Most of the benefits will be experienced by the utility and by society in general. However, the main benefit which can be expected from the smart grid is a reduction in power outages, which will mostly be of advantage for the electricity customers. Although reduced outages also mean that the utility will not lose out as much in electricity sales due to sustained outage times (Kempener, et al., 2015).

Table 4:1: Overview of the opportunities and challenges which smart grids present for developing countries. Information has been summarised from (Kempener, et al., 2015).

Opportunities	Challenges
Early stage grid development allows developing countries to **technology 'leapfrog'** and directly install smart grid technologies when building up their T&D network.	Utilities in developing countries are often **capital-constrained**, limiting their ability to invest into smart grid projects, even if they are economically viable.
Potential for innovative energy services such as linking payments to the mobile communications network, installing local charging stations, or using mini/micro grids for rural electrification.	**Upper cap on the utility tariffs** which can be charged so as still to remain affordable for the users. Therefore, difficult to retrieve O&M for the system.
Reduce technical and power theft losses in the power network. By recording electricity loads across the power lines smart grids can be used to track and reduce these losses.	**Lack of detailed data,** for example of the systems operation and consumer demographic. This kind of data is not readily available in all developing countries.
	Regulatory and institutional issues may limit innovation. For example: regional standards, harmonising of different power networks, ensuring data privacy.

Table 4:2: List of benefits when investing into smart grid technology in a developing country, sorted from highest benefit at the top to lowest benefits at the bottom (Kempener, et al., 2015)

Rank	Benefit	Primary Beneficiary
1	Reduced sustained outages	Costumers
2	Reduced electricity losses	Utility
3	Reduced CO_2 emissions	Society
4	Reduced ancillary service costs	Utility
5	Deferred distribution investments	Utility
6	Reduced SOx NOx and PM10 emissions	Society
7	Reduced equipment failure	Utility

Smart grid technologies present opportunities for both developed and developing countries. However, an IEA investigation into the driving factors for the adoption of smart grid technologies in developing economies revealed that these often vary in comparison to the drivers in developed economies (IEA, 2015a). Figure 4:1 shows a comparison of the main motives for smart grid investments in developed and developing countries. The comparison indicated that while improving system efficiency is important for both developed and developing countries, increasing system reliability and achieving secure revenue collection has a higher priority in developing economies, as oppose to developed countries (Varun, et al., 2016).

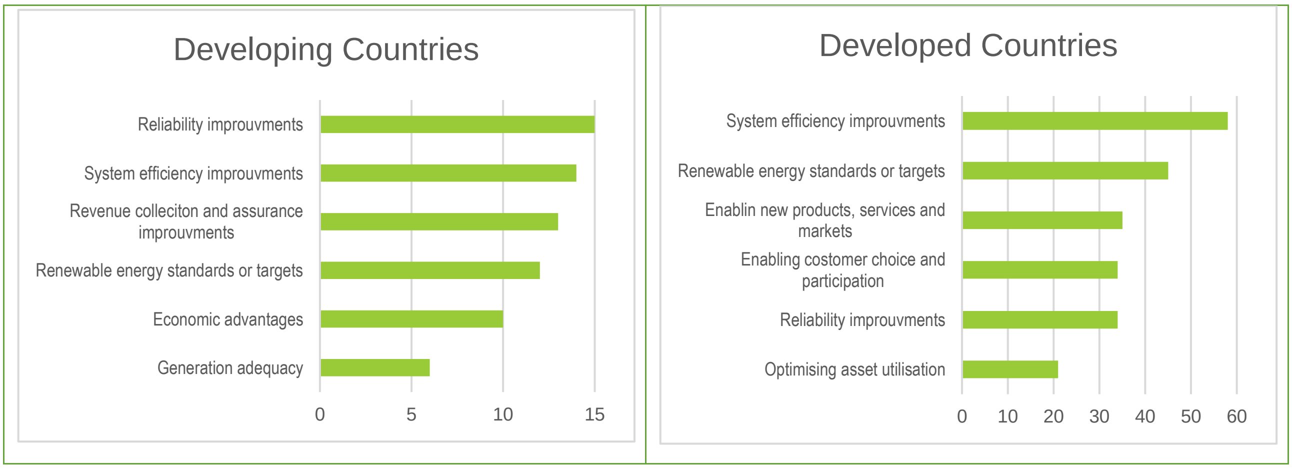

Figure 4:1: Comparing the main drivers for smart grid adaption in developing and developed countries. Date is based on a graph from (IEA, 2015b) which was originally adapted from (Wang, 2012)

Due to these differences drives for smart grid investment, developing countries also usually have different technological priorities when it comes to smart grids (Wang, 2012). Figure 4:2 shows a comparison of the technological priorities for smart grid installations in developing and developed countries.

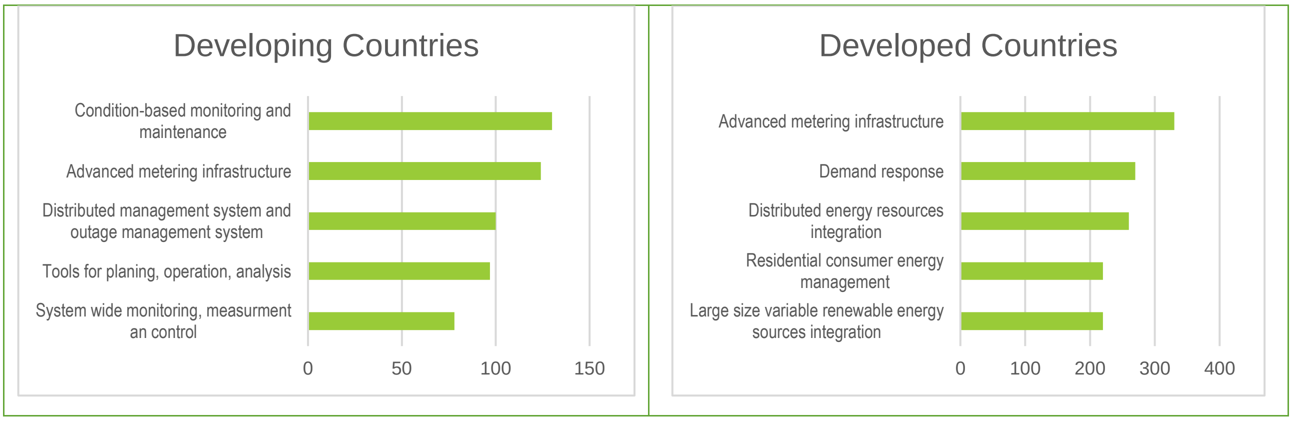

Figure 4:2: Comparing the technological priorities for smart grids in developing and developed countries (Wang, 2012)

Additionally, Table 4:3 lists a few of the common challenges faced by the electricity network in many developing countries and the respective smart grid solutions which can be used to address these challenges.

Table 4:3: Potential challenges in the electricity network and the corresponding smart grid solutions (IEA, 2015b).

Challenges in changing energy system	Smart grid solutions
Renewable and distributed generations	Balancing generation and demand, new business models
Limited generation and grid capacity	Load management and peak avoidance
Ageing and/or weak infrastructure	Reliability through automatic outage prevention and restoration
Costs and emissions of energy supply	Efficient generation, transmission, distribution and consumption
Revenue losses due to non-technical losses such as power theft	Full transparency and distribution level and automated loss prevention.

Overall this brief overview of smart grid technologies in developing countries shows that while there is a potential for smart grid development, projects implemented in developing countries need to be planned and assessed carefully. This is because different countries will have different expectations and requirements from smart grid technologies. Especially in developing countries it should be ensured that the roll out of smart grid technologies is tailored to the needs of the electricity network in question, so as to prevent ineffective investments of already limited capital. The studies reviewed in this section indicate that the main drivers for smart grid development in developing economies are reliability and efficiency improvements, as well as improving revenue collection. The integration of renewable energy generation, as well as opening new markets and increasing customer flexibility are much less of a priority for developing countries than they are for developed countries. Therefore, the needs of developing countries might well be met with a different layout of smart grid technologies than those often implemented in developed countries.

5 Investigating the Potential for Smart Grids in West Africa

Most studies seem to agree that there is a potential for smart grid technologies in the West African power grid. However, it is often emphasised that the demands for a smart grid system in West African countries will be different to those in most developed countries (Ma, et al., 2016). Therefore, it is important to develop a smart grid road map tailored to the needs of the region. It may be useful to consider experiences and lessons learned from other developed and emerging economies, however, these should not always be directly applied (Welsch, et al., 2013). Furthermore, it should be kept in mind that even amongst the WAPP member states there is a large range of electrification statuses and advances in grid development. Therefore, smart grid needs may further differ from country to country.

Generally, the demand for smart grids in most of Sub-Saharan Africa stems from a need to increase the amount of available capacity, reduce losses in the system and lower the cost of electricidal distribution and electricity tariffs in remote villages (Ma, et al., 2016). The smart grid approach for West Africa might consist of a balanced development of regional grid integration, national grid enhancement, and decentralised mini-grids (Welsch, et al., 2013). The smart grid interface and smart metering structures needed to serve the demands of the network will most likely not need to be as complex as those currently being developed in Europe or North America (Ma, et al., 2016).

At present, very few smart grid technologies have been implemented in West Africa, however, the "*topic is being actively discussed in the region especially in relations with renewable energy deployment*" (ECREE Advisor, 2017). Resources such as (Kotua, 2016) and (Kouassi, 2016) support this, showing that the potential for smart grid deployment is seriously being considered in some West African countries and that the first few pilot project have already been started.

Also in the global mini-grid sector smart grid technologies are still not the standard, however, they are increasingly being considered as an option for overcoming some common problems faced with revenue collection and maintenance issues (EnDev Mini-Grid Expert, 2017).

This section outlines some of the possible smart grid solutions proposed by various studies for the region of West Africa. In some cases, solutions proposed for developing countries outside of the region of West Africa will also be included, if the demands of the districted network are seen to be similar to those in West Africa. The break down for this section will be smart grid technologies for 1) transmission lines and substations 2) distribution systems 3) consumer side 4) mini-grids.

5.1 Transmission Network and Substations

Figure 5:1 shows the WAPP HV transmission network. Solid lines represent existing transmission lines, while dotted lines show where future transmission lines have been planned. The WAPP transmission network consists of two zones. The countries of zone A (Nigeria, Niger, Benin, Togo, Burkina Faso, Ghana, and Ivory Coast) are already interconnected. In zone B only Senegal and Mali are interconnected. The other countries in zone B (Liberia, Guinea, Sierra Leone, Guinea Bissau and Gambia) are not yet connected to the regional transmission network (WAPP, 2011b).

Currently the transmission network in the WAPP region is still very underdeveloped, both within the individual country boarders as well as for cross country transmission. The WAPP Master Plan from 2011 states that difficulties faced in the transmission network can be traced back to various problems such as a lack of fuel availability due to financing problems as well as the run-down state of existing equipment which has not been maintained properly. Furthermore, frequency control on interconnection lines between countries, as well as the risk of slow oscillation when major generation units go off-lien, are also listed as problems. Also, the lack of sufficient short-term power reserve in zone A limits the functionality of the interconnection lines between the countries. Due to these issues *"significant part of the installed capacity in production units in the area is currently unavailable"* (WAPP, 2011c).

Figure 5:1: Overview of the West African Power Pool high voltage transmission network (WAPP, 2011a)

In addition to these technical problems the grid also struggles with non-technical losses such as power theft, fraud, and non-payment of bills. The WAPP Master Plan includes a few suggestions for addressing these problems in the transmission network, however, smart grid technologies are not directly mentioned (WAPP, 2011c). This might be due to the fact that the plan is already a bit outdated and smart grid technologies where not yet as developed and readily available then as they are today.

Information gained from personal correspondence with an ECREE advisor (see Appendix A) indicates that while smart grid technology has been identified as an option for the transmission network in the WAPP region, its implementation is only happening very slowly. However, a few smart grid technologies have already been installed in the West African transmission network, such as new substations with a Supervisory Control and Data Acquisition (SCADA) systems (ECREE Advisor, 2017). SCADA system are often described as the brain of a smart grid, allowing for automated decisions to be made based on real-time data. Algorithms can be used to adjust the grid to disruptions, thus improving system stability (Remote Magazine, 2014).

In addition to the transmission problems mentioned above the WAPP Master Plan goes on to outline a few network constraints which the system will likely be facing during the deployment period of the planned expansion of the interconnecting lines between the WAPP member states. The following section examines how these different constraints might benefit from the implementation of smart grid technologies. Figure 5:2 shows the predicted regional trade between WAPP member countries in 2030, once the interconnecting transmission network has been expanded.

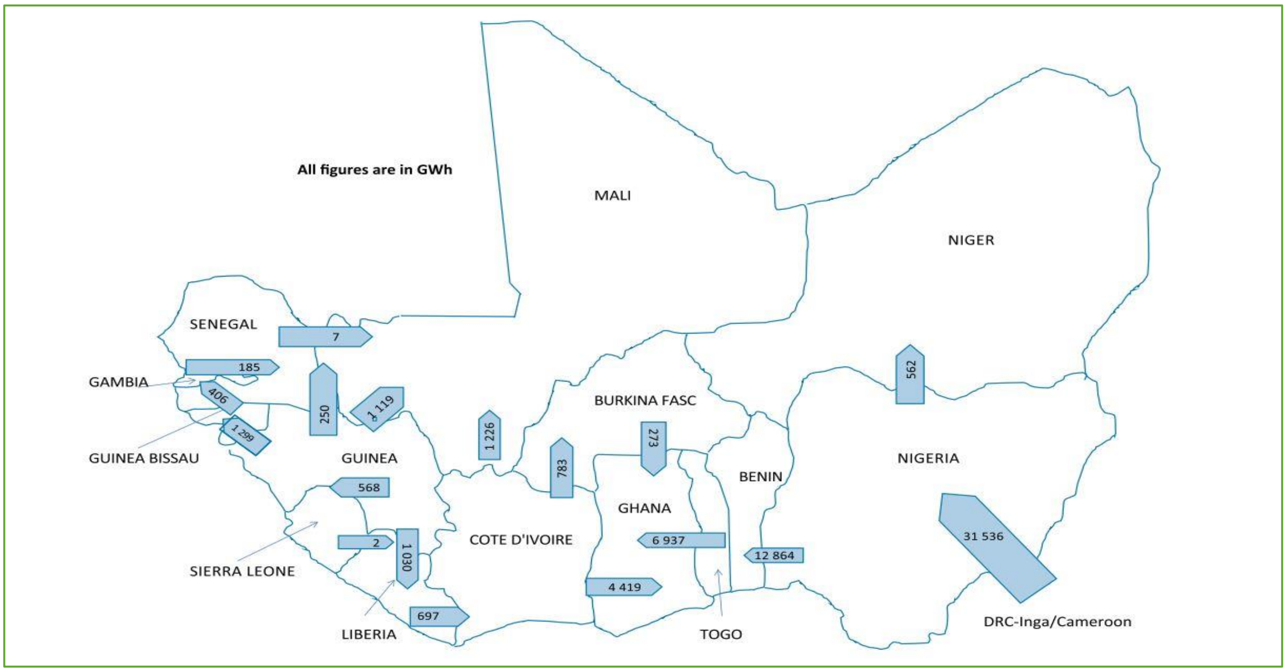

Figure 5:2: Predicted regional trade between WAPP member states in 2030 based on a renewable promotion scenario (Miketa & Merven, 2013)

5.1.1 Power System Stabilisers (PSS)

During the progressive interconnection stage the network is expected to go through a phase where it is less stable due to weaker interconnections. This will result in poorly damped oscillation due to long distances involved, thereby threatening the stability of the grid, potentially to the point that it can no longer operate properly. To counteract this the WAPP Master Plan proposes the installation of PSS on all currently operating large machines, as well as for all new machines being installed form this point onwards (WAPP, 2011d). PSS provide increased stability by damping generator rotor angle swings with broad frequency ranges (Green Energy Consulting, 2017). While not necessarily a smart grid technology, they can be integrated into smart grid controls systems using more advanced data processing methods to improve their performance (Horii, et al., 2013).

5.1.2 Under Frequency and Under Voltage Load Shedding (UFSL, UVLS)

The deployment of the current interconnection plan would remove necessary redundancy in the grid during the construction phase. To maintain a minimal amount of redundancy either large investments into the transmission network would have to be made, or special protection and defence schemes must be put in place which will have to be harmonised among the WAPP countries. This would consist of UFSL and UVLS, which could potentially also benefit from smart grid technology. Smart UFSL and UVLS system could use real time data to calculate the exact amount of load shedding required, based on the disturbance detected in the network as described in Charles et al. (2016) and Chuvychin & Petrichenko (2013).

5.1.3 WAPP Information and Control Centre (ICC)

The long distances which the interconnection lines will have to cover will affect the system stability which in turn will limit the exchange of electricity between the countries. This issue could be addressed by setting a maximum value for electricity transmission, however, this value would be very low since it would have to account for the worst-case scenario in terms of system stability. Therefore, in order to maximise transmission and still maintain system stability, the electricity exchange limits will have to be calculated regularly, using up to date data about the network conditions. This will require a form of smart grid control system with a functioning communication system that encompasses all WAPP countries. Day-ahead forecasts will be used to calculate the future stability limits. The WAPP Master Plan mentions that this could be achieved through the WAPP ICC (WAPP, 2011d).

5.1.4 General Overview of Smart Grid Technologies for the Transmission Network

Technical losses in the transition network as well as at substations can be very large, especially when long distances are covered. Smart grids technologies could be used to address this problem by facilitating maintenance schedules as well as improving the performance of power lines and transformers. This could, for example, involve the use of superconducting fault current limiting transformers as well as high-temperature conductors, dynamic line rating and FACTS. Data for the various sensors could be processed using wide-area monitoring to facilitate real-time decision making. However, advanced monitoring systems will depend on a roll out of smart grid technologies throughout the entire transmission system, which requires quite complex grid infrastructure and design (Welsch, et al., 2013). Therefore, while overall a very promising technology, it might not be feasible for the region of West Africa, with its currently still rather limited transmission network.

5.2 Distribution Network

Globally the uptake of smart grid technologies in the distribution network has been much slower to progress in comparison to the uptake in the transmission network (IEA, 2015b). This is because smartening the distribution network is more challenging than smartening the transmission network (IEA, 2011). However, there are many benefits of associated with smart distribution networks (Welsch, et al., 2013). The distribution network makes up the largest percentage of the total electrical system length and most of the electrical demand and renewable energy generation is connected to this section of the power grid (IEA, 2015b).

Some forms of smart grid control have already made their way into the West African distribution network. Based on information from ECREE some countries in the region have started to install *“transformers and meters that are equipped with data acquisition systems, allowing them to be accessed remotely through Global System for Mobile Communications (GSM). These can be used to detect power theft which can then be acted upon, thus reducing commercial losses in the distribution grid”* (ECREE Advisor, 2017). Figure 5:3 shows an image of smart meters which have been installed in the Ivory Coast to combat power theft and gather data on the operation the distribution network (Kouassi, 2016). High voltage distribution lines can also be used as a way of reducing power theft, as well as improving the quality and reliability of the power delivered (Welsch, et al., 2013).

Figure 5:3: Image of smart meters installed in a village in the Ivory Coast (Kouassi, 2016)

Further smart grid control in the distribution network could be achieved by Distributed Automation Systems (DAS). These usually consist of hardware, such as controllers, protective relays, reclosers, voltage regulator controls and fault circuit indicators, as well as some form of communication system. DAS can use network defined algorithms to create a system for fault detection, isolation and network reconfiguration. Furthermore, they can be used to collect general data on the distribution grid's operation patterns, which can be useful for operators and planners (Varun, et al., 2016).

Somewhat more simple smart grid technologies for the distribution network include smart sensors and flexible intelligent switches as well as interrupters installed at critical locations in the distribution network. These could help reduce power outages without resulting in high increases of consumer tariffs. Furthermore, smart grid technologies can be used to facilitate the integration of renewable energy generation into the distribution network. Especially in rural areas distributed generation can be used to increase energy access and avoid high connection coasts (Welsch, et al., 2013). For example, smart distributed PV inverters offer many advantages both financially, by offsetting the coasts of switch capacitor banks, as well as in terms of improving distribution line efficiencies (Kempener, et al., 2015).

5.3 Consumer Side

Customer side smart grid management, or Demand Side Management (DSM), often involves time-of-use tariffs or other forms of advanced pricing schemes which incentives a dynamic change in the consumer's electricity consumption which can be used to manage peak loads. This is often implemented through AMI (ECOWAS, 2015a). A further form of customer side smart grid involvement which is often mention is the use of smart appliance, which automatically switch on and off depending on current grid conditions. While in theory this sound very promising, the reality is that in most West African countries effective DSM is very difficult to achieve. This is because in many cases, especially in more rural areas, consumer energy use is very basic and usually only consists of lighting, fans, radios and occasionally TVs and fridges. Therefore, most of the load is naturally shifted towards evening times when people are at home and there is hardly any opportunity for extensive load shedding. Only in more urban areas, with larger loads and higher energy consumption for productive use, does DSM make sense (EnDev Mini-Grid Expert, 2017).

However, the idea of achieving DSM through the telecommunications network, which has been rolled out and adapted very successfully throughout Sub-Saharan Africa, is often suggested (Abdullah & Prof.Dwolatzky, 2009). A few projects have already been tested where consumers can access real time data on their energy consumption using their mobile phone. They can also top up their prepaid electricity meters using mobile phone credit. One example of a pilot project has been mentioned in which a household's grid connection has an upper capacity limit. If this capacity is exceeded by the user, the system trips and they automatically receive a text message alerting them of the problem and instructing them to disconnect one of their devices in order to be reconnected. Models such as this are seen as promising for future smart grid management through consumer involvement (EnDev Employee, 2017). A further example of smart grid technology installed on the consumption side of the network is shown in Figure 5:4. It is a remote management and monitoring system for street lights installed in the Ivory Coast. The system is used to oversee the performance of the street lights as well as to alert the operator of when a failure occurs and maintenance is needed (Kouassi, 2016).

Figure 5:4: Remote management and monitoring of street lights in the Ivory Coast (Kouassi, 2016)

5.4 Smart Mini-Grids

Mini-grids are mentioned in virtually all studies which concentrate on electrification in West Africa. Large portions of West Africa's population still live in remote and rural area, although this is starting to change (Escudero, et al., 2017). This rural demographic is often best served through standalone mini-grids, rather than through expansions of the national power grid, which are often economically unfeasible as well as taking a long time to realise (EnDev Mini-Grid Expert, 2017). Furthermore, long transmission lines into remote areas will result in high losses (Temitope, et al., 2016). Therefore, many studies suggest a 'bottom-up' electrification approached, as illustrated in Figure 5:5 below. This approach suggests that developing and emerging economies can make use of smart grids to build up from household electrification systems to community and regional systems. For this to be feasible standards must be set for these mini-grids, which will allow them to one day be seamlessly connected with the next larger grid. Each successive upscaling can increase the grid's reliability and availability of power (IEA, 2011).

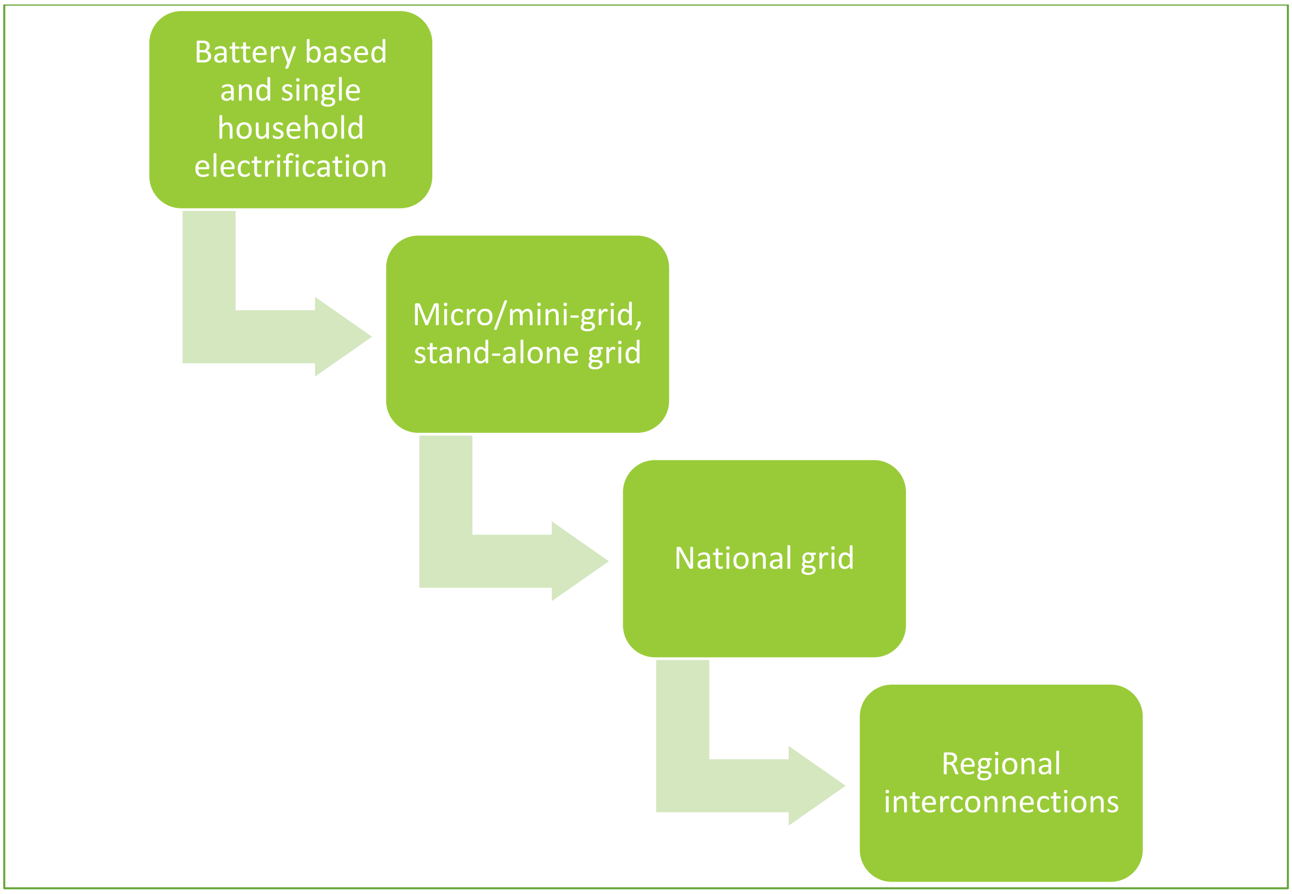

Figure 5:5: Outline of a potential rural electrification pathway in developing counties (IEA, 2011)

Despite the numerous advantages which mini-grids present for rural area, most studies see them only as a mid-term solution, to provide basic energy access until the main utility network can be expanded into these remote areas. Especially in countries experiencing strong economic growth this might prove to be the more advantageous option, since larger grids can offer more stability (Welsch, et al., 2013). Naturally, the prospects for upgrading a mini-grid system to a main grid connected system will depend on the specific circumstances of the mini-grid involved, such as the distance from the main utility network as well as the demographical development in that area. A combination of these factors could be used to determine whether future upscaling of the mini-grid is likely or not (EnDev Mini-Grid Expert, 2017).

Some experts, however, completely distance themselves from this approach and instead suggest long term planning for stand-alone mini-grids. They argue that the concept of the centralised grid network is outdated and inefficient and that well managed smart mini-grids, or even stand-alone renewable energy devices, offer more advantages, even in the long run. It has been suggested that with the current development of smart grid technologies, developing economies can leapfrog the traditional power network structure and use smart control systems to develop distributed energy system to their full advantages (SolaPak, 2016; Sebitosi & Okou, 2010).

In either case, mini-grids must be able to operate effectively off the central grid for the upcoming years, ideally offering more reliable access to electricity for rural populations. Smart grid technologies can be implemented to achieve this, by increasing the performance standards for mini-grids. This mainly involves incorporating technologies which can be used to even out fluctuation supply and demand conditions, for example through advanced load control strategies instead of conventional load shedding (Welsch, et al., 2013).

Additionally, smart grid technology, especially AMI can be used to improve the financially viability of mini grids. Currently many mini-grids which have already been installed in West Africa struggle to remain operational because the consumer tariffs do not cover the O&M costs for the grid. While international donor funding is often available for the construction of rural mini-grids, few donors are willing to commit to regular payments for the upkeep of the systems. AMI could be used to monitor the O&M coasts and achieve more secure revenue collection which will allow for more sustainable and long term operation conditions. Prepaid metering systems have been identified as a very promising solution for addressing financial viability problems. This is mainly because they offer a good payment option for rural populations without a stable monthly income and because they create a direct link between costs and electricity consumption, which furthermore encourages efficient consumer behaviour (EnDev Mini-Grid Expert, 2017). Secure revenues for mini-grid developers mean that they are more likely to invest in further mini-grid projects, thus contributing towards achieving universal energy access in the region (Welsch, et al., 2013).

6 CONCLUSION AND RECOMMENDATIONS

A combined overview of the energy situation in West Africa, as well as the potential advantages of smart grid technologies, shows that many of the problems currently being faced by the electricity sector in West Africa could be addressed through smart grid solutions. The general literature review on smart grid implementation in developing countries shows that the deployment of some smart grid technologies may benefit the performance of the electricity grid in developing countries. However, the review also highlights the importance of tailoring smart grid solutions specifically to the needs of each individual country. This is to ensure that limited capital is invested effectively.

Focusing in detail on the smart grid potential in West Africa shows that there are various possible applications for smart grid technologies through the West African grid, including the transmission network, the distribution network and the customer side of the grid. Especially in long-distance transmission networks, smart grid technologies have the potential to reduce the high losses currently occurring as well as to improve overall system stability. In the distribution network, there is a need for smart grid solutions to prevent power theft and fraud, as well to facilitate the integration of new distributed renewable generation capacity. On the customer side the application of smart grid technologies is slightly more limited, however, the potential for combining smart grid solutions with the telecommunications network to improve consumer involvement seems promising. Furthermore, smart grid technologies can provide many advantages for the stable operation of mini-grids. Mini-grids can be used to increase energy access in rural area, integrate new renewable energy generation and facilitate a ‘bottom-up’ electrification approach. Furthermore, there is a large demand for AMI to ensure the financial viability of mini-grids.

The main challenges facing the roll out of smart grid technologies are similar to the barriers for reaching the ECOWAS renewable energy and energy efficiency targets, as outlined in section 3.1.3. This includes problems with weak policies and regulations, lack of financial investment as well as the general insufficient availability of data on the energy sector in West Africa. An increase in data available on the West African energy sector would have many advantages for the facilitation of new energy projects in the region. Reliable data might allow for new, better informed, policies to be created as well as increasing the confidence of potential investors. This could help the development of smart grid technologies in the region. However, the lack of data available for the electricity network in West Africa could in fact also be used as a driver for the investment in smart grid technology, since an increase in smart grid technologies throughout the grid would also result in a greater availability of data.

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APPENDIX

A) EMAIL CORRESPONDENCE WITH AN EMPLOYEE OF THE WEST AFRICAN POWER POOL

Sent on the 21st of March 2017, following an Interview with another WAPP employee

"Smart grids is a topic that is being actively discussed in the region specially in relations with renewable energy deployment but being only slowly being implemented, for example I would the new sub-stations of Sakete (Benin) and other similar sub-station recently financed by development partners in the regions all include a control system SCADA (Supervisory control and data acquisition) which is one of the corner stone of a smart grid.

There are many countries e.g. Cote d'Ivoire and Ghana, that are introducing Transformers and Meters that are equipped with data acquisition systems that can be accessed remotely through GSM which allows them to know if people are stealing power, so reduction of commercial losses in distribution grids, and allow them to take corrective actions.

Attached are two presentation, the first one specifically on smart grids from the perspective of the African Electrotechnical Standardization Commission (AFSE) and the second one by CIE in Cote d'Ivoire which is talking about the use on smart meters to reduce distribution losses.

So all in all the discussion is happening and with new electricity dispatch centre being built in many countries the region is slowly entering the smart-grid era."

B) Renewable Energy Resources in West Africa

Solar

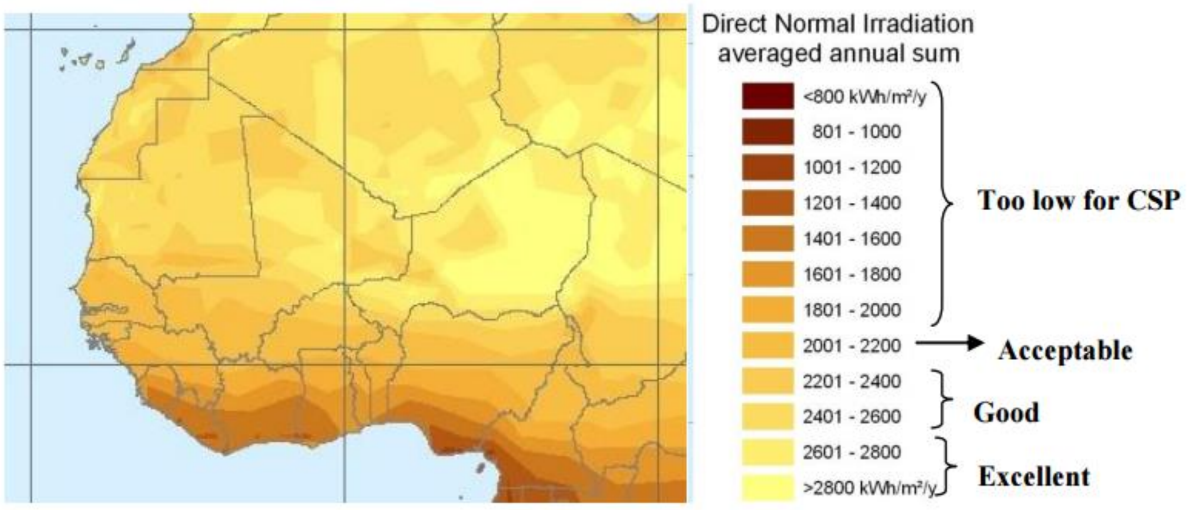

Figure 0:1: Solar Resource Map of West Africa (WAPP, 2011b)

Wind

Country	Average wind speed (m/s)	Generation (MWh/an/MW)	Comment
	Wind resources of best identified sites (see maps in appendix)		
Senegal	6	2588	
Gambie	6	2588	
Guinea-Bissau	5	1717	This generation level is usually considered to low for investment
Guinea	8	4051	
Sierra Leone	too low	x	No feasable wind project
Liberia	too low	x	No feasable wind project
Mali	7.2	3531	
Ivory Coast	4.8	1565	This generation level is usually considered to low for investment
Ghana	6	2588	
Burkina Faso	6.5	2999	
Togo	5.8	2451	
Benin	6.5	3006	
Nigeria	7.8	3933	
Niger	8	4051	

Figure 0:2: Estimated Wind resource for each of the WAPP member states (WAPP, 2011b)

C) SUPERVISION RECORD FORM

1st Meeting

Dissertation Supervision Record Form
Academic Year 2016-17

Name of Student:	Johanna von Behaim	Name of supervisor:	Peter Connor
Topic of dissertation:	Smart Grids in Benin Developing Countries		
Summary of meeting (if desired)	· First meeting. · Discuss topic, what it might include, how it might be developed.		
Actions to be taken by the student	· Do some initial research into the topic. See if I am interested		
Date:	23/09/2016	Signature of supervisor:	

2nd Meeting

Dissertation Supervision Record Form
Academic Year 2016-17

Name of Student:	Johanna von Behaim	Name of supervisor:	Peter Conner
Topic of dissertation:	Smart Grids for Improved Grid Performance in Developing Countries		
Summary of meeting (if desired)	Meeting to discuss the requirements for the dissertation planning proposal as well as talking about the possibility of narrowing down topic to researching smart grid control for mini-grids.		
Actions to be taken by the student	• Finish writing planning proposal • Think about conducting interviews in Benin. Start planning this as well as writing the necessary Risk Assessment. • Look in to the possibility of including some grid-modelling.		
Date:	03.11.16	Signature of supervisor:	

3rd Meeting

Dissertation Supervision Record Form
Academic Year 2016-17

Name of Student:	Johanna von Behaim	Name of supervisor:	Peter Connor
Topic of dissertation:	Smart Grids in Benin		
Summary of meeting (if desired)	• Meeting to catch up on progress • Post interview: talked about how to incoperate information from the interview into the report.		
Actions to be taken by the student	• Process interview information • Finish writing report		
Date:	27/03/2017	Signature of supervisor:	[signature]

4th Meeting

Dissertation Supervision Record Form
Academic Year 2016-17

Name of Student:	Johanna von Behaim	Name of supervisor:	Peter Connor
Topic of dissertation:	Smart Grids in Benin		
Summary of meeting (if desired)	· Final meeting · Discuss final formatting / layout questions + logg-book hand-in.		
Actions to be taken by the student	· Finalize report. · log-book not required, but could collect all notes and still hand it in.		
Date:	31/10/2016	Signature of supervisor:	[signature]