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Exploring the nexus of mini-grids and digital technologies

Potentials, challenges and options for sustainable energy access in Sub-Saharan Africa

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The content of the study as well as any flaws it may have are the sole responsibility of the authors.

Abbreviations

ANN	Artificial neuronal networks
BMZ	Federal Ministry for Economic Cooperation and Development
DLT	Distributed ledger technologies
ECOWAS	Economic Community of West African States
GIS	Geographic Information System
GIZ	Gesellschaft für Internationale Zusammenarbeit GmbH
GNI	Gross National Income
ICT4D	ICT for development
ICTs	Information and communication technologies
IEA	International Energy Agency
IoT	Internet of things
IRENA	International Renewable Energy Agency
IT	Information technology
ITU	International Telecommunication Union
NREL	National Renewable Energy Laboratory
PAYG	Pay as you go
PUE	Productive use of energy
PV	Photovoltaic
REA	Rural Electrification Agency
RISE	Regulatory Indicators for Sustainable Energy
RLI	Reiner Lemoine Institute
RMS	Remote monitoring system
SADC	Southern African Development Community
SCADA	Systems control and data acquisition
SDGs	Sustainable Development Goals
SHS	Solar home systems
SSA	Sub-Saharan Africa
SWARM	Site Wizard for Analysis, Reconnaissance and Mapping
TaTEDO	Tanzania Traditional Energy Development Organization
UASF	Universal access and service funds
UNIDO	United Nations Industrial Development Organization
USAID	United States Agency for International Development
WDI	World Development Indicators

Executive Summary

Access to clean, reliable and affordable energy is one of the key challenges for many countries in Sub-Saharan Africa. This is particularly the case in rural and remote areas which are often not connected to the national main grid. Mini-grids are expected to play an important role in providing access to sustainable and reliable energy in these areas. On the other hand, this report argues that mini-grids also need to meet a set of key requirements to become future-proof and contribute to the achievement of the United Nations Sustainable Development Goals (SDGs). Mini-grids should foster the integration of renewable energies. They should provide for equitable and affordable electricity costs and reliable electricity supply. They should be sensitive to the specific local context and foster the development of productive uses. Moreover, they should be flexible and adaptable to changing conditions, such as new technologies, increasing demand and the arrival of the main grid, and account for transparency and consumer protection. Finally, mini-grids should be designed in a way which reduces their ecological footprint as far as possible.

Over the past years, the mini-grid sector has seen an increase in the use of digital technologies while at the same time digital innovations transform the socio-economic landscape in Sub-Saharan Africa. In light of these developments, the report explores how digital technologies could be applied to mini-grids to help meet the requirements mentioned above. The study identifies two levels of application for digital technologies in mini-grids: 1) the level of technical functionalities and system balancing which includes generation and storage, distribution and control as well as demand side management; and 2) the level of the mini-grid value chain, which includes finance, planning and design, operation and maintenance, customer management and the productive use of electricity.

Across these application areas, digital technologies have the potential to provide solutions that enable more efficient and time-saving processes, reduce costs as well as improve services for the consumer. However, the use of digital technologies in mini-grids in rural Sub-Saharan Africa also poses new challenges and risks, in particular with regards to privacy and data security, and requires a high level of awareness for the creation of user-centric technologies. If the potentials are exploited and risks mitigated, digital technologies could contribute to achieving future-proof mini-grids that serve sustainable development in rural Sub-Saharan Africa. However, many of the potentials that could unfold through the integrated use of digital technologies in mini-grids have not yet been tapped into. Technical issues, even internet access, do not appear to be limiting factors for the application of digital technologies in mini-grids. Regulatory, economic and socio-cultural framework conditions play a much more decisive role.

Against this backdrop, policy-makers, donor organisations and technology developers should collaborate to create favourable framework conditions and new impetus for a purposeful use of digital technologies in mini-grids. Amongst others, policy makers should provide long-term plans for grid extension so that mini-grid developers are able to evaluate the extent to which it makes sense to incorporate digital technologies. Policy-makers should further provide incentives and subsidies for projects serving the testing of digital solutions, develop suitable regulatory frameworks and support the development of technical standards and quality criteria. They also should

develop legal frameworks for data security and consumer protection. Donor organisations could contribute to the meaningful use of digital technologies in mini-grids by including technical requirements for appropriate digital features in mini-grid tenders and incentivizing or even requiring that data from the mini-grids they fund is shared. They should further foster the collaboration between communities, innovators and local researchers, and support the creation of knowledge about the effects of digital technologies in mini-grids, for instance on costs, long-term sustainability, consumer satisfaction and the creation of productive uses. Lastly, companies and technology developers should always put consumer needs at the centre of technology development and consider the specific local contexts. They should engage in jointly developing standards that benefit the whole sector, embrace using open-source software and share their data and experiences from successes and failures.

1. Introduction

Background

Access to clean, reliable and affordable energy is one of the key challenges for many countries in Sub-Saharan Africa (SSA). This is particularly the case in rural and more remote areas which are often not connected to the national main grid. For these areas, decentralised energy technologies can provide viable solutions for energy access. Mini-grids are expected to gain an increasing role in this regard as they – other than solar home systems (SHS) – not only serve the electricity demand of small households, but also provide enough energy for productive uses [1], for example in manufacturing, farming and agro-processing.

Over the past decade, the digitalisation trend has entered the mini-grid sector leading to the development of innovative approaches and technologies to improve mini-grids and related services [2]. In parallel, modern information and communication technologies (ICTs), in particular mobile phones and smartphones, continue to spread to even remote and rural locations in Sub-Saharan Africa opening up new possibilities for productive uses of energy (PUE).

Objectives

Against this backdrop, this report aims to shed light on two issues:

1) the different use cases of digital technologies across the value chain of mini-grids, and

2) how they may assist mini-grids in meeting the requirements of sustainable development.

In this regard, particular emphasis will be given to the promotion of productive uses of electricity in rural areas. Aside from potentials, the study also takes a critical look at possible challenges and risks of the increasing use of ICTs in mini-grids. In this sense, the study aims to provide a comprehensive overview of the interlinkages of digital technologies and mini-grids as well as their contribution to achieving the United Nations Sustainable Development Goals (SDGs, see Box 1).

Scope of the study

The study focuses on Sub-Saharan Africa, the region which is still most challenged by a lack of energy access in particular in rural and remote communities. Since frameworks and conditions vary substantially across Sub-Saharan Africa, Annex I of the report provides detailed factsheets on ten Sub-Saharan African countries, namely Ethiopia, Kenya, Madagascar, Mali, Mozambique, Nigeria, Senegal, Tanzania, Uganda and Zambia highlighting key aspects, such as access to electricity and internet penetration. The factsheets also provide an overview of the countries' rural electrification status, digital development strategies and mini-grid policies. The ten countries were selected in order to cover a wide range of country contexts and different levels of diffusion of mini-grids and ICTs.

Box 1: A glimpse at the SDGs: Linking affordable energy access, sustainable infrastructures and climate action

The 2030 Agenda for Sustainable Development provides essential guidelines for international efforts to foster a comprehensive, global transformation towards sustainability. Its 17 Sustainable Development Goals (SDGs) address a broad range of topics, such as poverty, hunger, health, water, energy, education, gender equality, reduction of inequalities, economic development, biodiversity and climate action.

The topic of this study links particularly to three SDGs. It addresses SDG7 which targets affordable and clean energy since mini-grids enable access to electricity from renewable energy sources to some of the most vulnerable and marginalised people. In this sense, mini-grids provide an essential infrastructure for economic development and human well-being, a core element of SDG9. Innovative digital technologies could make these infrastructures more sustainable and reliable and improve the services offered by them. Furthermore, where mini-grids are powered by renewable energy sources, they not only contribute to SDG7, but also to the implementation of SDG13 promoting climate change mitigation.

Approach

We assume that mini-grids (see Box 2) and digital technologies are deeply embedded in societal contexts which include social and cultural norms, values and practices as well as economic, regulative, financial, infrastructural and policy aspects. Societal framework conditions and human actions therefore shape the design, production and use of technologies. In return, technological changes and new developments also have an impact on the social system linked to them [3]. This socio-technical approach allows a more comprehensive look at technological solutions and their potential opportunities and challenges which, in turn, contributes to providing more sustainable and socially accepted solutions [4].

Methodology

This study is based on information from three main sources: firstly, it draws on the literature on mini-grids and rural electrification as well as ICT for development (ICT4D). We considered academic literature as well as reports and studies by leading international organisations in these fields. Given the amount of literature on the topics relevant for this study, the literature review does not claim to be complete. Nevertheless, by assessing the latest studies as well as a broad range of publications on the aforementioned topics, we have managed to gain an overview of the main findings and current state-of-the-art in research on mini-grids and digital technologies in development contexts.

Secondly, between March and May 2019, we conducted 14 interviews with experts from GIZ and UNIDO and other donor organisations as well as representatives from companies and technology developers working on mini-grid technologies (see Annex II). The interviews were semi-structured and adapted to each interviewee's individual expertise. The interviews served to collect information on the interlinkages of digital technologies and mini-grids, whilst gaining insights into practical experiences in several of the focal countries of this study. Amongst other questions, the interviewees were asked how they perceive the relevance of digital technologies for the improvement of mini-grids as well as their opportunities for productive uses of energy. Furthermore, challenges and potential benefits of digital technologies in mini-grids were discussed with the experts.

Finally, we organised a workshop on 9 May 2019 in Berlin where the preliminary results of the study were presented to 16 experts from BMZ, GIZ, UNIDO as well as technology developers, innovators and other experts from the digitalisation and energy fields. The workshop served to discuss and enrich the findings from both the literature review as well as the interviews conducted at this point of time. Furthermore, together with the participants, options and recommendations for different stakeholder groups were developed.

Structure of the report

The study is structured as follows:

- Following this introduction, Chapters 2 and 3 provide basic background information on the status quo and deployment of mini-grids as well as ICTs in Sub-Saharan Africa.
- Chapter 4 elaborates in more detail the requirements that mini-grids should fulfil in order to become future-proof and contribute to the achievement of the SDGs.
- Chapter 5 analyses how digital technologies can be used to improve mini-grids across their value chain and how ICTs could contribute to the productive use of energy. It further discusses opportunities and challenges, taking technical as well as socio-economic aspects into account.
- Chapter 6 draws conclusions and reflects on how digital technologies could contribute to meeting the aforementioned requirements for sustainable mini-grids.

- Chapter 7 provides options for action to make better use of the potential synergies between mini-grids and digital technologies in Sub-Saharan Africa. This section particularly addresses policy-makers, donor organisations as well as companies concerned with innovations for mini-grids and productive uses of energy.
- The Annex provides detailed profiles of the selected focal countries and an anonymised list of interview partners we spoke to for this study.

Box 2: What is a mini-grid?

The term mini-grid used in this study is understood as “a set of electricity generators and possibly energy storage systems interconnected to a distribution network that supplies electricity to a localized group of customers” [5]. The size of mini-grids usually ranges between 10kW and 10MW. Mini-grids can operate in isolation from national electricity transmission networks [6]. Very often, instead of “mini-grids”, the term “micro-grids” is used. While some see a difference between these two expressions, we view them as interchangeable and use the term mini-grid in this report.

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2. Mini-grids for sustainable energy access

2.1 Electricity access in Sub-Saharan Africa

Over 590 million people, more than half of the population, are without access to electricity in Sub-Saharan Africa with over 80 per cent of those living in rural areas [1]. Figure 1 provides an overview of rural electrification in Sub-Saharan Africa, highlighting the figures for ten focal countries. Whereas the average rural electrification rate in Sub-Saharan Africa is below 25 per cent, this rate lies at approximately 71 per cent in urban areas [1]. Removing this rural-urban divide is challenging, as the dominant electrification strategy – extending the national grid – is not always suitable to reach remote and sparsely populated rural communities [7–10]. Here, public and private actors alike encounter a host of physical, financial, regulatory and technical challenges which hinder grid extension.

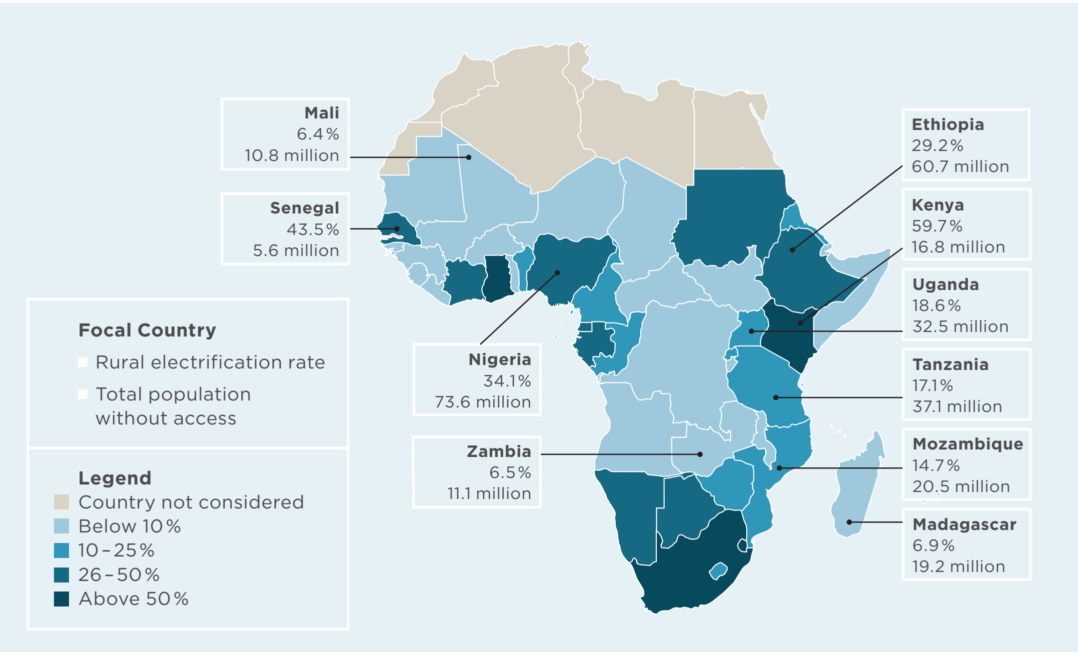

Figure 1: Rural electricity access map (2016)

Source: Own figure based on IEA, Energy Access Outlook 2017 [1].

Next to the challenges of extending the grid, the central power supply has severe reliability issues in most Sub-Saharan African countries. Since much of the infrastructure is old, badly maintained and in need of new investment, many areas suffer from frequent and long power outages. Public utilities often struggle to work cost efficiently and consumer tariffs need to be subsidised to remain affordable [12]. Due to the challenges of conventional electrification through grid extension, rural households and businesses often remain un-electrified and depend on traditional energy sources (e.g. firewood or kerosene lamps) or expensive and polluting small-scale diesel generators. In contrast, a shift towards off-grid electrification, e.g. through solar home systems and mini-grids based on renewable energy technologies, opens up new opportunities for cheaper, faster and cleaner electrification [13].

2.2 Mini-grid deployment in Sub-Saharan Africa

Due to falling photovoltaic (PV) and battery prices in the last years, solar-based and hybrid mini-grids have become a promising new option for energy access in rural and remote areas. In a policy scenario for Sub-Saharan Africa developed by the International Energy Agency (IEA) in 2014 [14], it was estimated that up to 140 million rural inhabitants may be serviced by mini-grids by 2040 – necessitating the deployment of between 100,000 and 200,000 mini-grids. Numerous countries in Sub-Saharan Africa have integrated off-grid renewable energy solutions into their national electrification strategies and mini-grids have been piloted and deployed across the region. However, the prevalence of mini-grids in Sub-Saharan Africa differs largely from country to country. For instance, in a study on mini-grids in the Economic Community of West African States (ECOWAS), the number of mini-grids reported in different countries ranged from below 5 in some countries to over 100 in others [15]. Whilst these numbers are dynamic and constantly changing, they also highlight how differences in demand, infrastructure and regulatory frameworks influence the diffusion of mini-grids. In the cases of Senegal and Mali – where mini-grids seem to be more prevalent – both governments set up initiatives to support off-grid solutions already over a decade ago [15]. In Kenya, it is estimated that if recommended regulatory changes are implemented, the number of mini-grids could reach 2,000 to 3,000 by 2021 [16]. As another example, due to recent policy changes the mini-grid sector in Nigeria is growing with the country being seen as having a high potential for the large-scale deployment of mini-grids in the future [17].

2.3 Challenges for mini-grids

Despite increasingly favourable conditions for mini-grids, there remain a number of obstacles. First of all, the deployment of mini-grids is still largely donor-driven or dependent on subsidies. Moreover, it strongly depends on countries' regulatory environments [18]. According to the World Bank's Regulatory Indicators for Sustainability (RISE) scorecard, Sub-Saharan Africa is the region with the weakest regulatory environment with half of the countries deemed to have an underdeveloped policy framework and only one country, South Africa, with a more advanced one [19]. The lack of a clear policy environment, however, heightens uncertainty and deters private investments [20].

A further key issue for the long-term viability of a mini-grid concerns the question of whether and when the national grid will arrive in a given area. Since consumers tend to prefer to be serviced by the central electricity grid due to lower costs and higher trust in the quality of the service provided, there is the possibility that a previously installed mini-grid may become a stranded asset once the main grid reaches a community.

Besides, there remain technical difficulties associated with setting up and maintaining mini-grids in rural areas in the long run, also in light of consumer protection. The initial deployment of mini-grid solutions requires a high amount of technical expertise which is often provided by external actors due to a lack of capacity and knowledge on the local level [9]. Therefore, once the mini-grid is set up, communities are commonly still reliant on external repair and maintenance services which, given their often remote location, leads to significant delays. Technical failures, often due to inadequate maintenance and a lack of quality of components, is a common fate for many mini-grids in Sub-Saharan Africa. Flawed technical and safety standards and the resulting technology failures decrease trust on the side of the consumers. Quality assurance for mini-grids is therefore a central issue for their long-term sustainability [21].

In summary, mini-grids need favourable and reliable national regulations, adequate incentives and subsidies as well as reliable information on the long-term plans for national grid expansion. Further enablers for the successful implementation of mini-grid projects are the thorough consideration of the specific needs and aspirations of the affected communities as well as reliable information about their actual and future electricity demand. Finally, mini-grids also need agreed technical standards and certification mechanisms to ensure certain safety and quality levels – an important element guaranteeing the social acceptance and backing of rural populations.

Box 3: Environmental challenges of mini-grids

Adequate end-of-life management of mini-grids still poses a significant challenge to the environmental sustainability of mini-grids. Mini-grids powered by renewable energy are considered a climate-neutral technology, but of course, the production and disposal of the relevant equipment – from cables to switchboards to solar panels – has an ecological footprint. Mini-grid equipment may fail, in many cases due to a lack of proper maintenance, and is often improperly disposed, risking adverse health effects for people and the emission of environmentally harmful substances. Especially batteries should be disposed adequately [22]. Proper end-of-life management is therefore a key component of sustainable mini-grid solutions.

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Deep read: Favourable framework conditions for mini-grids are still a major challenge. A broad range of publications addresses this issue in-depth. For example, the 2018 study of IRENA "Policies and regulations for renewable energy mini-grids" [20] explores elements of enabling environments and policy measures for mini-grids and discusses them on the basis of eight case studies of countries in Sub-Saharan Africa, Asia and Latin America. The report "Accelerating Mini-Grid Deployment in Sub-Saharan Africa: Lessons from Tanzania" [23] published by the World Resources Institute and TaTEDO in 2017 looks at one specific country-context and formulates recommendations that could also be useful for other Sub-Saharan countries. The 2018 report "Tariff considerations for micro-grids in Sub-Saharan Africa" [24], published by USAID, Power Africa and NREL, takes a deep dive into the issue of adequate tariff setting in mini-grids. The Mini-Grid Policy Toolkit Portal [25] furthermore provides a comprehensive collection of policy examples, case studies and support tools to make mini-grids more attractive.

IRENA (2018): Policies and regulations for renewable mini-grids. Abu Dhabi.
Odarno, Lily et al. (2017): Accelerating Mini-Grid Deployment in Sub-Saharan Africa. Lessons from Tanzania. World Bank. Washington, D.C.
Reber, Tim et al. (2018): Tariff considerations for micro-grids in Sub-Saharan Africa. USAID, Power Africa, NREL.
EU Energy Initiative Partnership Dialogue Facility (EUEI PDF): Mini-Grid Policy Toolkit. Available online at http://www.minigridpolicytoolkit.euei-pdf.org.

2.4 Productive use and community engagement

Gaining access to electricity is often assumed to lead to the productive use of energy which, in turn, boosts people's businesses and income-generating activities [26–28]. In the context of Sub-Saharan Africa, where the main livelihood activity is farming [29], productive use of energy particularly includes the automation of work processes such as milling and irrigation [30] – whilst also enabling the use of machinery and tools to enhance productivity and efficiency. Outside of the agricultural sector, people can benefit from lighting to, for instance, keep their shops open longer whilst also offering electrified services such as printing.

However, productive use should not be seen as an inevitable outcome of electrification. In a number of studies, it has been shown that consumers may prefer to use electricity for household lighting, entertainment and communication [31]. In many contexts, a lack of business skills and awareness of how to optimise work processes through electrification hinder productive use, whereas limited access to financial capital in rural areas also limits entrepreneurs in upscaling their activities [7,32]. Structural factors including poor market access and susceptibility to climate-induced shocks such as droughts and crop failures furthermore exacerbate people's reluctance to invest in expanding and automating their income-generating activities.

Furthermore, a lack of understanding of the lifestyles and habits of the local population may lead to interventions which are not aligned with communities' interests and preferences [33]. This can undermine the success and functioning of mini-grids including the productive use of energy due to a lack of trust and acceptance of new technologies in communities. It has also been shown that limited knowledge of the local context could lead to interventions which exacerbate existing inequalities and conflicts. For instance, one prevalent issue is that often only wealthier groups are in a position to benefit from the provision of electricity services. It has also been shown that the positive effects of electrification in rural areas are often split unevenly between women and men (see Box 4).

Accordingly, the prior analysis of such potential risks and challenges, the identification of specific priorities of the affected communities as well as the formulation of strategies and mechanisms to account for these need to be part of the design and deployment of mini-grids in rural Sub-Saharan Africa. Including community members early in the design and implementation phases of mini-grids can enhance trust and acceptance and enable the design of an intervention which responds to the needs of the community. This is not only relevant for local social and cultural issues. It also gives planners and implementing actors a better picture of the type of financing schemes, technical design, educational interventions and support for productive uses which are needed to make the project successful.

Box 4: Considering gender issues in mini-grids

Empowering women is a common objective of many rural electrification projects. Yet, there exist only few studies that empirically analyse the effects of rural electrification interventions on gender issues [34], even less take a specific look at the impacts of mini-grids. A study on the implications of electricity access for women's empowerment in rural Kenya found out that interventions, even if taking a gender-neutral approach, often produce systems dominated by men and reproduce gender stereotypes, such as women caring for households while men engaging in productive work [35]. The study suggests that centring on women's needs, participation and leadership in rural electrification processes could increase the likelihood of success of the intervention and strengthen benefits for the whole community. In another recent study [36] evaluating a solar mini-grid that had been set up in Mpanta in rural northern Zambia, it was found that electrification has different impacts on women and men – and may even exacerbate inequality. Especially if decision-making procedures are dominated by men, the way in which a mini-grid is set up is likely to corresponded more to male preferences than to those held by women in a community.

In conclusion, electrification projects cannot be assumed to automatically enhance gender equality and women's empowerment. They should therefore be aware of possible gender divides and be accompanied with specific interventions aimed at addressing gender issues already during the design and implementation phases.

3. ICTs and digital development in Sub-Saharan Africa

3.1 Digital change in Sub-Saharan Africa

In the late 1990s, many African countries started to formulate national ICT strategies. These strategies were particularly centred on the development of adequate telecommunication infrastructures, the improvement of education and training as well as the promotion of economic opportunities from ICTs to participate in global knowledge economies. Furthermore, they aimed at decreasing inequalities and improving ICT access and skills of marginalised groups, such as young people, the rural poor and women [34].

Over the past decade, ICT policies gained traction amid the increasing importance of the internet, its easy accessibility through smartphones, the use of apps as well as technological advances in areas such as big data and artificial intelligence. Digital transformation has in many Sub-Saharan African countries become a central issue for national socio-economic development. This goes along with a focus on providing more suitable framework conditions not only for the development of digital skills, but also for digital innovations. Creating a favourable ecosystem for innovative tech start-ups, e.g. through suitable legislation, financial incentives and funding opportunities has therefore become an important aspect in national ICT and digital development strategies in many Sub-Saharan African countries. This can also be seen in the flourishing of technology hubs and co-working spaces in countries like Kenya, Uganda, Nigeria, Senegal and Ghana [42].

3.2 ICT adoption and prices

Today, mobile phones are commonly used throughout the region. According to a report by GSMA, the number of unique mobile subscribers totalled 444 million in 2017 which amounts to 44 percent of the population in the region [37]. By 2025, this number is expected to rise to 634 million which would represent 52 percent of the population [37]. One major driver of this development concerns decreasing prices for mobile phones and telecommunication services. For example, between 2008 and 2016, the mobile-cellular basket price of the ITU decreased to 3.8 USD which is less than the world average and one of the lowest prices worldwide [38].

The number of smartphones, despite being more costly, is also growing strongly. By the end of 2017, it has already reached 250 million and is likely to double by 2025 [37]. Computers, on the other hand, are not widely used in Sub-Saharan Africa. Only an 8.8 percent of households in Africa owned a computer in 2017, compared to the world average of 46.9 percent [39].

With regard to the internet, the region is still largely disconnected. Between 2013 and 2017, the number of people using the internet almost doubled and reached 22.1 percent of the population [39] (see also Figure2). Still, this is less than half of the world average of 48.6 percent [39].

According to the International Telecommunication Union (ITU), broadband internet is still costly although prices have decreased in the past years [38]. Significant price reductions in a number of African countries contributed to an overall regional downward trend in fixed broadband prices. Yet the region still ranges highest worldwide, both in absolute and relative terms [38]. Prices for mobile broadband, on the other side, lie below the world average at 8 USD for the prepaid handset-based and 15 USD for the postpaid computer-based sub-basket [38]. However, it is noteworthy that the minimum and maximum prices in the region are far apart [38].

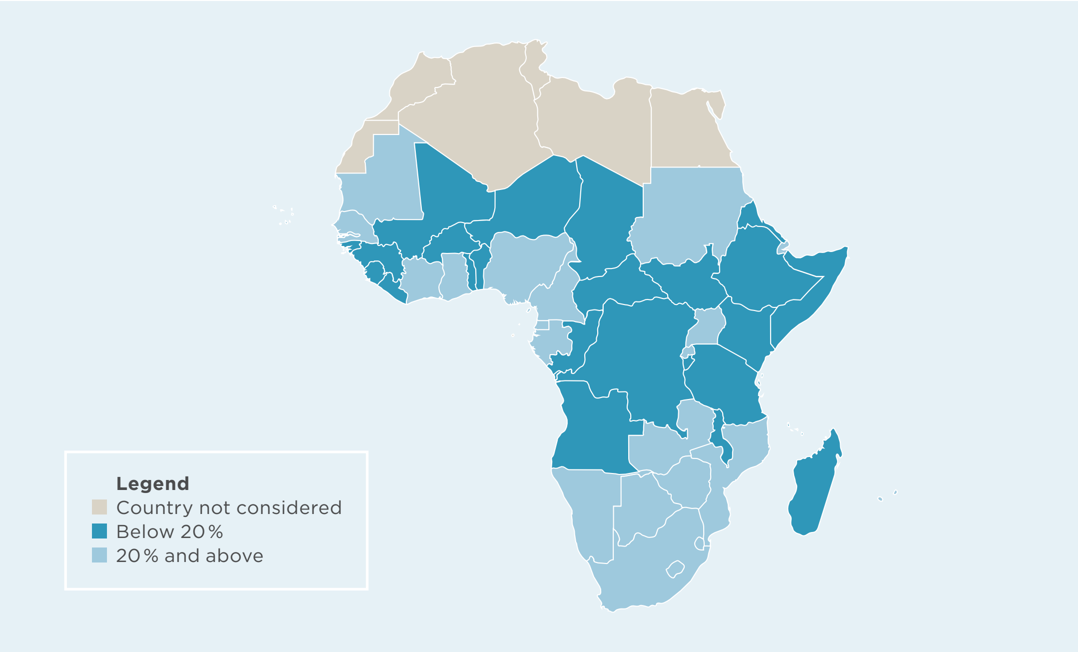


Figure 2:
Countries where less than 20 % of the population use the internet (2017)

Source: Own figure based on World Development Indicators (WDI), World Bank [11].

3.3 Economic, social and ecological impacts of ICTs

Modern ICTs are perceived as having a positive influence on the socio-economic development of rural communities. For example, ICTs provide access to market information for farmers and allow a comfortable and quick exchange between businesses and their customers, whilst also providing access to information that can help to improve services and goods. Furthermore, applications for mobile payments, for example M-Pesa, enable the economic integration of individuals without a bank account which is a widespread challenge in Sub-Saharan Africa.

However, despite these manifold positive practical examples, the scientific literature is inconclusive with regard to the social and economic effects of ICTs and their role in decreasing inequalities [40]. Similar to energy access technologies, ICTs do not automatically generate an added benefit for their users. Indeed, there are indications that ICTs and internet connectivity could increase existing inequalities which often exist along socio-economic groups with regard to gender, age and education [41]. ICTs therefore need to be assessed within their social setting as they may amplify existing divides. Being aware of such potential adverse effects is decisive for the use of ICTs in the context of development projects [42].

In addition, national regulations also affect the extent to which modern ICTs can be used for economic purposes. For example, mobile money services such as pay-as-you-go (PAYG) solutions for energy access are much more prevalent in Eastern Africa, than in many West African states (see Figure 3) [43]. One important reason for this difference is that many East African countries have more favourable regulatory conditions with lower entry barriers and risks for companies providing such services.

The increasing spread of digital services and business models further necessitates regulations for the protection of data and privacy of consumers and users of ICTs and related services. As of March 2019, 17 Sub-Saharan African countries have enacted data protection laws whereas seven were in the process of drafting and nine had no legislation in place [44]. In 2014, the African Union adopted the Convention on Cyber Security and Personal Data Protection which how-

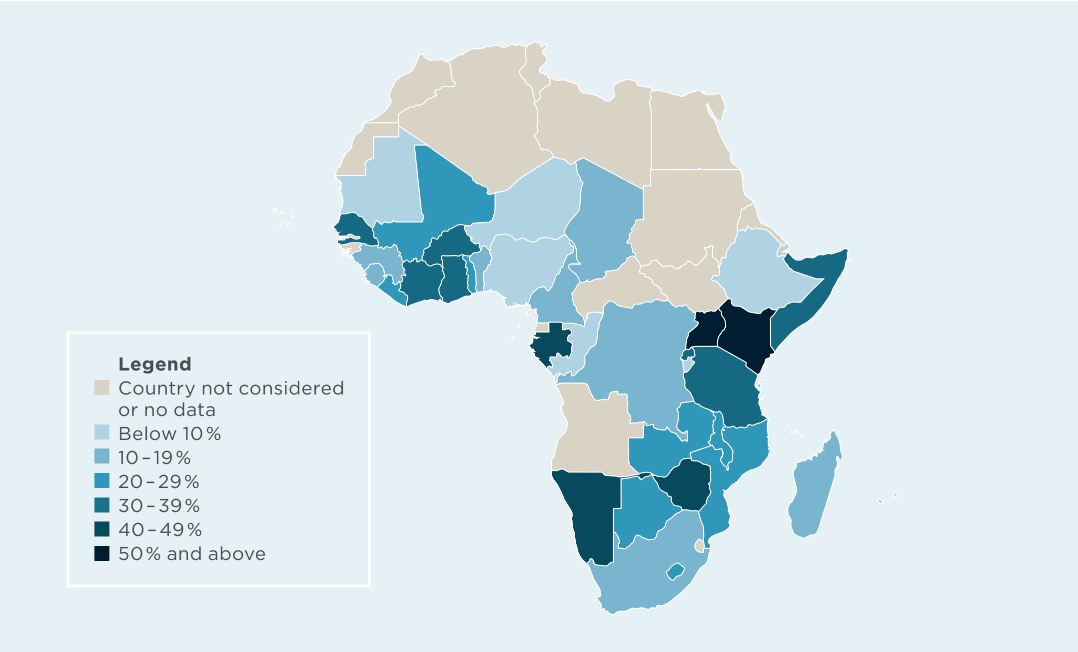


Figure 3: Mobile money account penetration in Sub-Saharan Africa (2017)

Source: Own figure based on World Development Indicators (WDI), World Bank [11].

Due to a lack of availability, the data for Somalia and Burundi are taken from the year 2014.

ever has so far only been signed and ratified by a small number of Sub-Saharan African countries [45]. On the regional level, there are several initiatives working towards data protection, for example a mode law developed by the Southern African Development Community (SADC) which includes data protection or a supplementary act on personal data protection put together by the Economic Community of West African States (ECOWAS) [45].

Last but not least, ICTs have a considerable ecological impact. In particular the extraction and processing of resources for ICTs and the manufacturing and assemblage of components play a decisive role in the emission of greenhouse gases related to ICTs [46]. Countries in Sub-Saharan Africa which provide essential resources for the production of digital technologies do not only bear the ecological, but also the heavy social burdens of irresponsible and unsustainable raw material extraction. Moreover, e-waste – both exported to as well as produced in Sub-Saharan African countries – becomes a mounting challenge. In 2016, Africa (including North Africa) was accountable for 2.2 million metric tons of e-waste [47]. However, with 1.9 kg of e-waste generated annually per inhabitant, Africa ranges well below the global average of 6.1 kg per inhabitant [47]. The disposal of e-waste is largely left to the informal sector, creating enormous health risks as well as social and environmental challenges [48,49]. While the recovery of precious metals such as gold, silver and palladium could present itself as an opportunity, African governments are often overburdened by ensuring adequate e-waste regulation and its enforcement and struggle with a lack of financial means and the provision of incentives for proper e-waste treatment. Still, awareness for this topic is growing across Sub-Saharan Africa with countries like Ghana, Kenya, Nigeria and South Africa spearheading the development of legislation in the region [47].

Against this backdrop, the development and implementation of ICT interventions need careful consideration and responsible action, especially in development contexts and when addressing marginalised and vulnerable people (see Box 5).

3.4 Challenges for rural connectivity

Similar to electricity infrastructure, the costs for telecommunication services are mediated by factors such as location and distance from urban centres as well as population density and the nature of the terrain. While many urban areas in Sub-Saharan Africa today have relatively well established telecommunication infrastructures, including broadband internet access, remote and rural areas often remain underserved. In developing countries, mobile networks are therefore frequently used to provide digital infrastructures to disconnected areas [31]. Still, a significant digital gap remains between urban and rural areas. Many Sub-Saharan African countries have set up Universal Access and Service Funds (UASFs) to finance the extension of telecommunication services to underserved communities. However, with the increasing relevance of broadband, these funds face many challenges in a new rapidly developing and complex environment [32].

On the user level, the affordability of ICTs still remains a challenge. Mobile-cellular prices as a percentage of GNI per capita decreased from 28 percent to 9 percent between 2008 and 2016 [30]. Yet, this is still three times the world average. Similarly, the price of broadband in Africa is far above the world average. In Africa, the prepaid handset-based mobile-broadband sub-basket calculated by the ITU reaches 8 per cent of GNI per capita whereas in the rest of the world the value is below 5 percent [30]. In terms of fixed broadband, only six countries in the region offer plans that represent 5 percent of GNI per capita or less [30]. The affordability of the internet therefore still poses a major challenge, especially for low-income and often rural populations. It therefore contributes significantly to the digital divide within Sub-Saharan African countries.

Aside from infrastructural gaps and affordability challenges, connectivity faces high social and cultural obstacles in rural areas. Literacy rates are often significantly lower than in urban areas whereas access to education and training is limited. These factors hamper the adoption of ICTs and their application for productive uses. Furthermore, only a limited amount of content on the internet is provided in local languages [51] and even less specifically targets rural populations, thus limiting the value that people gain from ICTs and the internet.

Box 5: Principles for Digital Development

Based on their rich practical experiences from ICT interventions, a broad range of members of the international development community have developed nine Principles for Digital Development [50]. These principles are intended to strengthen the benefits of ICT projects for the affected individuals and communities while mitigating potential adverse effects and risks. Among others, they highlight the need for a user-centric design of ICT projects which pays attention to the specific local contexts. Furthermore, the principles underscore the importance of issues like data security and privacy and emphasise that ICT systems should be built in a sustainable way, meaning that they continue to function reliably and provide benefits to their users even after the official end of the intervention. Furthermore, the Principles for Digital Development promote the use of open software and the sharing of experiences and data.

4. Requirements for sustainable mini-grids

Renewable mini-grids offer various opportunities to improve rural livelihoods in Sub-Saharan Africa. Although scaling up this technology is generally desirable, it is also clear that mini-grid projects are inevitably confronted with numerous economic, social and environmental challenges as outlined above (see Chapter 2.3). Next to challenges with regards to suitable framework conditions, mini-grids also need to meet certain expectations in order to become future-proof. From the interviews and discussions held with various stakeholders and experts over the course of this study, a normative catalogue of essential characteristics was developed. It contains conditions and requirements which need to be fulfilled by mini-grids in order to support the implementation of the UN SDGs, in particular SDGs 7, 9 and 13:

1) **Mini-grids should be powered by renewable energy sources.** The guiding principle for planning new mini-grid projects should be that only renewable energy sources (e.g. solar, wind, hydro) are considered for electricity generation. When older, existing mini-grids with diesel generators are retrofitted with renewable energies ("hybridisation"). The design needs to increase the renewable share to the highest extent possible.

2) **Mini-grids should account for the specific socio-economic context.** Mini-grids must be tailored to the (often harsh) operation conditions in rural areas in Sub-Saharan Africa. Therefore, technology and operational management must be state-of-the-art and designed to serve specific user needs. This necessitates community engagement during the planning and design phase. Besides, electrical safety standards need to be respected. The implementation of technological improvements should be possible with reasonable effort.

3) **Mini-grids should enable equitable and affordable electricity costs.** Mini-grids generally need to be designed in a cost-efficient manner whereby the average cost of electricity needs to be as low as possible. All consumers should pay an equitable (and potentially also a temporally variable) electricity price for the electricity supplied by the mini-grid. Power producers and operators should likewise receive an equitable and temporally variable remuneration for the electricity fed into the mini-grid.

4) **Mini-grids should provide reliable electricity supply.** High reliability and quality in power supply are essential requirements for mini-grids. Ultimately, a 24/7 power supply without voltage and frequency fluctuations should be targeted to supply not only households, but also productive user (cf. 5). The reliability of decentral electricity supply can be an important competitive advantage compared to the central grid system where power outages are a frequent problem in many Sub-Saharan African countries.

5) **Mini-grids should be oriented towards productive uses.** Mini-grids, especially in the context of Sub-Saharan Africa, are more than just a means to satisfy the electricity demand of households. They should encourage the development of new businesses and economic activities in agriculture, manufacturing, commerce and services and thereby increase the economic welfare of a community. From the outset, planners should always consider this and orient system sizing and design towards the potential productive use of consumers.

6) **Mini-grids should adapt to new conditions.** Mini-grids should be designed to allow if not even promote a flexible, demand-driven expansion at later stages. For this purpose, there need to be uniform interfaces and equitable access to the grid with all network participants having the same rights and obligations to operate and expand their capacity. Furthermore, mini-grids should enable new modes of interaction within the grid by, for instance, allowing electricity consumers to also act as producers and thus "prosumers". Furthermore, the mini-grid design should allow for the possibility to connect to the public power grid at any time so that potential investors are not deterred by a possible future arrival of the main grid.

7) **Mini-grids should guarantee transparency and consumer protection.** All relevant operational data (technical and commercial) should be automatically recorded and clearly documented. At the same time, it is essential that individuals' data privacy is protected and that the data is adequately accessible for consumers. For the latter point, it would for instance be desirable to provide the information in the local language. Economic decisions, for instance tariff setting, need to be communicated in a transparent manner whereas payment systems should also be transparent, traceable and user-friendly. An independent arbitration entity should be set up to settle potential disputes.

8) **Mini-grids should minimise their ecological footprint.** Mini-grids should generally be designed for a long service life. For the selection of key components, quality and ecological criteria need to be applied. Mini-grid projects must also include a recycling concept and provisions for the avoidance of electronic waste.

Against the backdrop of this list of requirements, it is relevant to consider which role digital technologies could play in achieving them. Before diving into this issue, Chapter 5 outlines the various applications of ICTs throughout the value chain of mini-grids.

5. Applications of digital technologies in mini-grids

For decades, ICTs have been used to improve energy systems with the energy sector often acting as an early adopter of new information technologies [52]. In the past years, digital innovations (e.g. in the field of artificial intelligence and big data), advances in computing as well as the reduction of costs for digital technologies have opened up new possibilities for the digitalisation of the energy sector. In particular the creation and analysis of vast amounts of data as well as the connection of different "smart" devices to become an internet of things (IoT) promote the idea of a more flexible and efficiently manageable energy system. Such a system would also be better suited to handle increasing complexity, especially regarding the integration of renewable energy sources and multiple, often small renewable energy producers [53].

The implementation of mini-grids based on renewable energies in Sub-Saharan Africa provides a potential application area for digital technologies. Mini-grids, especially those being powered by intermittent renewable sources, require smart and digital technologies to balance electricity demand and supply and to ensure an efficient system operation. In addition, digital innovations can address other challenges by for instance optimising project development processes, improving the design and planning of mini-grids as well as improving maintenance, management and customer related processes. Furthermore, the integration of digital technologies in mini-grids could contribute to the development and promotion of productive uses of energy.

Figure 4 illustrates the application areas where digital innovations may provide added value for mini-grids. Overall, two levels of application can be distinguished which include different sub-categories:

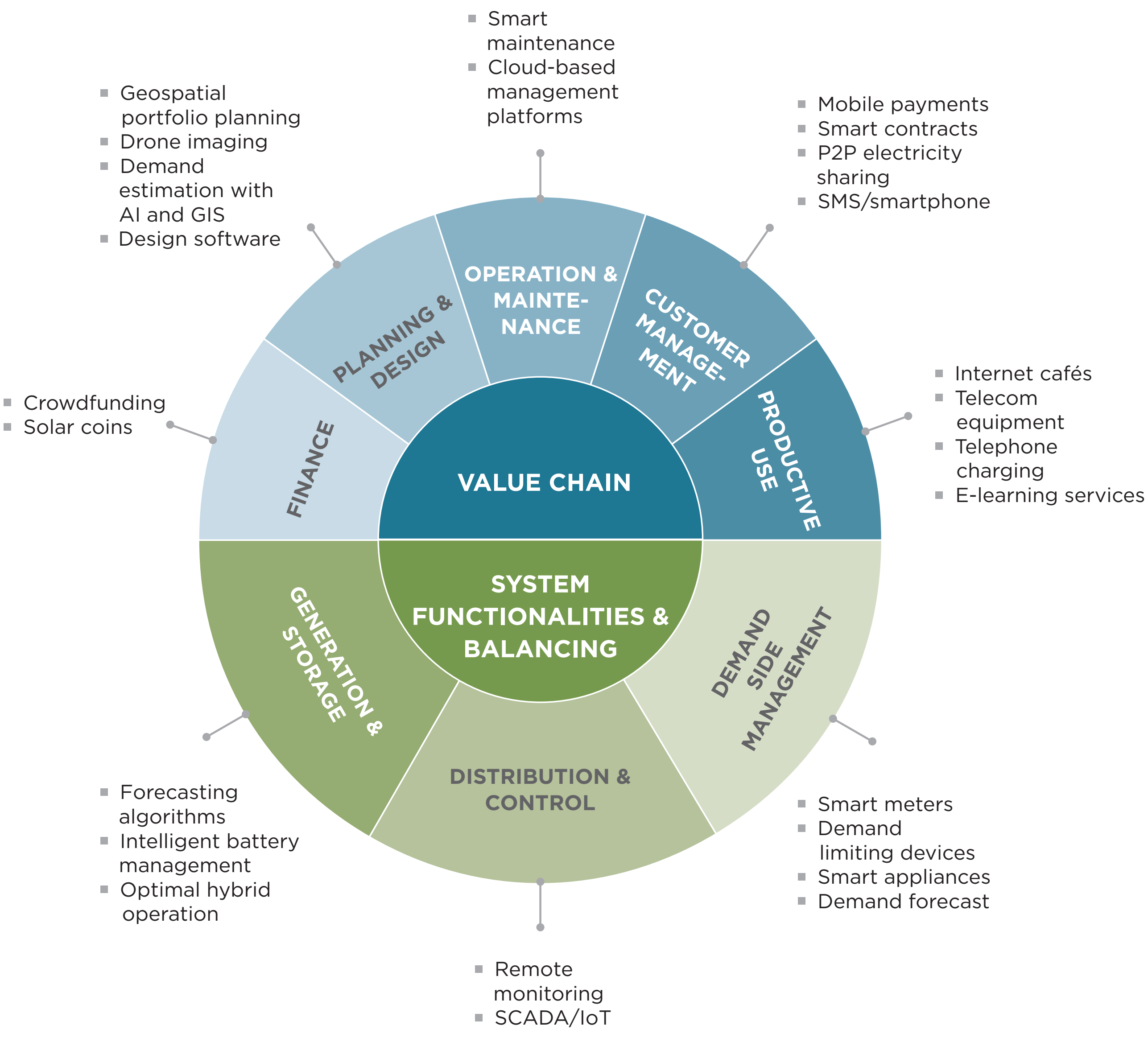
1) Technical functionalities and system balancing, including
- Generation and storage
- Distribution and control
- Demand side management

2) Applications on the level of the mini-grid value chain such as
- Finance
- Planning and design
- Operation and maintenance
- Customer management
- Productive use of energy from mini-grids.

In the following, we will discuss each category, starting with the level of digital technologies for system functionalities and balancing as the underlying technical substructure of mini-grids.

Figure 4:
Application areas of digital technologies in mini-grids

Source: Own figure.



5.1 Digital technologies for system functionalities and balancing of mini-grids

In terms of system functionalities and balancing, digital technologies help to optimise the key technical operations of the system, mainly by improving the balancing of generation, storage, distribution and consumption of electricity ("supply-demand-management"). Like all power systems, mini-grids must ensure that electricity generation equals demand at any moment of time. In "traditional" mini-grids this power balancing is performed by a central generator (e.g. diesel generator) whose output simply follows the electricity load of the users. With the trend towards more and more decentralised and intermittent renewable generation, battery storage and potentially even prosumers becoming constituents of mini-grids, the balancing challenge has grown to become a complex optimisation problem. Smart digital technologies are the means to address this challenge.

Generation and storage

There are several ways how the generation and storage system of mini-grids can be made "smart" with digital technologies. Mini-grids that are mainly powered by intermittent renewable generation technologies (e.g. photovoltaic generators, wind turbines) can for instance profit from weather forecasting algorithms based on numerical prediction models. These can be treated by the energy management system to compute power generation forecasts, enabling the mini-grid controller to automatically optimise the use of battery storage and/or the deployment of diesel generators in hybrid systems [55]. Smart inverters in combination with batteries could further improve the control of the generator and thus provide not only power but also system stability services.

The use of renewable energy in mini-grids increases the complexity of the systems. Smart mini-grid controllers can handle not only uncertainty on the demand side but also on the supply side. They help to maximise the utilisation of renewable resources and keep fossil fuel consumption low, e.g. in diesel hybrid systems.

Distribution and control

Digital technologies enable a better control of the distribution grid and power distribution to the consumers. Real-time management of grid parameters, such as voltage, frequency, active and reactive power flows, as well as the detection of failures can be improved with the help of distributed sensors placed at various points of the system. These include transformers, busbars, switchgears and distribution panels. Moreover, digital technologies for distribution and control could also enable flexible switching between electricity supply from the mini-grid and supply from the main grid (in cases where the mini-grid is connected to the national grid).

In a wider sense, smart meters and even intelligent appliances (see next section) also become part of this network of intercommunicating IoT devices. Next generation system control and data acquisition (SCADA) allow for real-time processing of these data and may be possibly assisted by remote management platforms or cloud-based monitoring systems [8] (see also Chapter 5.4).

Deep read: The "Innovation Outlook: Renewable Mini-grids" [54], published by IRENA in 2016 provides a comprehensive overview of technology developments in renewable mini-grids. It explores trends and developments in areas such as planning and design, generation, storage, control and management as well as consumption and discusses how these could enable faster commercialisation and large-scale deployment of renewable mini-grids. The study furthermore provides recommendations for key players to drive innovation in mini-grids.

IRENA (2016), Innovation Outlook: Renewable Mini-grids, International Renewable Energy Agency, Abu Dhabi.

Demand side management

Another important aspect of a mini-grid's system functionality concerns IT-assisted demand side management. Managing the demand of household consumers, small and medium enterprises, or community-operated equipment for productive use, like grain mills or water-pumping facilities, can significantly improve the technological and economic performance of mini-grids. One enabler for smart, IT-assisted demand side management could be flexible tariffs, i.e. electricity prices that continuously change throughout the day according to algorithms assessing the current energy status of the system. The idea is that these price signals would incentivise consumers to shift their power consumption to hours of the day, where enough energy is available. Such smart management could reduce stress on the system, and increase the life-span of essential and important components of the mini-grid, in particular batteries by improving their charging cycles, and thus reduce costs [56]. Advanced smart meters are capable of limiting the power consumption of users as a function of user priority and the available energy of the overall system. Examples of technology providers of smart meters for mini-grid demand side management include INENSUS [57], Powerhive [58], Circutor [59] and EarthSpark International [60]. Especially in rural contexts, however, such technologies must ensure that they fit the needs and capacities of the users to gain their acceptance [56]. In the case of peer-to-peer electricity sharing (see Chapter 5.4), smart meters can also be used to promote electricity trade among distributed prosumers.

Another aspect of demand side management includes household appliances. Household appliances are getting more and more attention by developers of mini-grids as energy efficiency is a key issue in rural electrification. For instance, the internet platform Efficiency for Access [61] provides an inventory of energy-efficient appliances for rural areas. In theory, all devices with smart grid access could become part of an intelligent mini-grid control regime which remotely controls their loads to match renewable generation. However, experts have identified only a few examples – concerning for instance high-level devices such as freezing units – where it would make (economic) sense to integrate appliances with communication functions into mini-grids [8].

The final aspect of demand side management concerns electricity load forecasting which is equivalent to power generation forecasts (see section "Generation and storage"). Forecasting methods, based on artificial neuronal networks (ANN) and fuzzy logic algorithms learning from customer behaviour have been discussed to a certain extent in scientific research on mini-grids [55,62], but it is unclear whether any field tests, especially in Sub-Saharan Africa, have ever been performed.

5.2 Digital technologies for financing mini-grids

Key components of financing mini-grids include raising investment capital and reducing investors' risks. Regarding de-risking, digital technologies can play a crucial role by increasing the transparency of project development and assessment processes which, in turn, ultimately leads to lower investment risks for external parties. In addition, the massive amount of data created on potential mini-grid sites, resource availability and customers' ability to pay allows for a more efficient remote assessment of the financial viability of projects.

Digital technologies could also provide new possibilities for raising funds for mini-grids. In recent years, several initiatives have financed mini-grids through crowd-funding campaigns via online platforms such as Bettervest [63], Ecoligo [64] or Crowd4Climate [65]. While crowd-funding campaigns can be helpful in covering the high initial costs of mini-grids, there is little known about how the long-term financial challenges of mini-grids may be resolved by these initiatives. For example, it is unclear how they address the potential gap between the actual costs of providing electricity through a mini-grid and the often limited ability of customers to pay for the services.

Several approaches for financing energy access have further evolved with the emergence of distributed ledger or blockchain technology (see Box 6) and the possibility to issue tokens in exchange for renewable energy generation. Examples in this area include SolarCoin [66], The Sun Protocol [67] as well as XiWatt [68]. These solutions provide an innovative approach in linking digital assets and financial assets with social assets. However, they often face a lack of understanding and confidence from the side of regulators and donor organisations and are therefore still a niche development.

5.3 Digital technologies for the planning and design of mini-grids

Digital technologies come into play at various stages of the planning and design processes of mini-grids. For instance, geospatial portfolio planning, based on satellite data, digital maps and image recognition, helps to identify locations suitable for electrification through mini-grids [70] (see Box 7). Such planning tools are usually used for site identification and macro-planning on the regional or even national level. They may furthermore help to avoid the setting up of mini-grids in areas which may soon be serviced by the national grid and speed up the planning and design processes [71]. The US-based company Powerhive [58] is an example of a mini-grid provider which makes use of geospatial planning tools.

However, even when using such tools, mini-grid providers are often still faced with the challenge that there is a lack of available and affordable high-quality data [72]. In particular granular socio-economic data, concerning for instance customers' ability to pay or the location of facilities and small businesses, often still needs to be gathered manually which can be both time-consuming and resource-intensive [72,73]. To counter this issue and obtain useful data, there have also been attempts to use drone-image assisted planning. The French company ENGIE developed a tool called Taos.ai [74] which uses such an approach to generate optimised mini-grid designs. Drone or high resolution satellite images are processed to identify locations of future customers and to optimally plan the distribution grid and connection rates. In practice, however, there still appears to be a mix between digital and conventional data collection methods for mini-grid planning and design [72].

In addition, self-learning algorithms support the demand and load estimation and even anticipate the customers' willingness to pay during project design, thereby assisting conventional mini-grid planning software, such as HOMER [75], in the sizing of the generation system and the distribution grid. Digitalisation can work towards more holistic planning, where site identification, demand estimation (including big data

Box 6: A glimpse at blockchain technology

Blockchain or distributed ledger technologies (DLT) have received wide attention in recent years as an innovative solution to provide a reliable, incorruptible, decentralised database that allows transactions between individuals who do not know and therefore do not trust each other. Usually, such transactions – including transfers of money, properties and legal titles such as land rights – require a neutral intermediary to establish trust and document the transaction. Typically such a role is taken on by a bank, a notary or a public administration. However, the intermediary often creates dependencies and additional costs and may even be susceptible to fraud and corruption. These issues are addressed by the blockchain technology which provides a technical solution for direct transactions between individuals that does not require an intermediary. Blockchain substitutes the function of an intermediary by using a network of nodes that validate and store information in a decentralised and transparent way. Because of this, information once saved in the blockchain cannot be tampered with.

In recent years, blockchain technology has been tested in various international development projects, e.g. for financial services such as the transfer of remittances, peer-to-peer electricity trading and the management of land titles and identities. However, currently, there is very little reliable information available about the impacts and lessons-learned from these applications [69].

analysis), resource and technology cost assessment, sizing and optimisation, as well as financial modelling and tariff setting (e.g. with loop to the demand estimation) are integrated into one single planning tool. Attempts to establish such holistic planning solutions are for instance made by the US-provider Odyssey [76], which has developed a digital, web-based platform for planning and managing mini-grid projects.

5.4 Digital technologies for operation, maintenance and customer management

With regards to operation and maintenance as well as customer management, digital applications interact more profoundly with the socio-economic and country-specific context of a mini-grid project.

Box 7: Using GIS for site identification

Project development for mini-grids in remote and rural areas is associated with high development and transaction costs. In many cases, expensive field trips and surveys are required to understand the local situation and demand for electricity at the very early project development stage. This significantly increases the developers' risk as they have to pre-finance such activities before knowing about the viability of the sites.

This risk can be reduced by using remote site identification tools. Geographic information systems (GIS) can be used to process geospatial data and subsequently identify suitable settlements for mini-grid developers. Crucial information such as the number and location of households, population density and existing grid infrastructure can be obtained from sources like OpenStreetMap or via automatic detection on satellite images. After the remote identification of settlements, household figures can be linked to socio-economic data and customer profiles derived from existing projects. This is made possible by the use of smart meters which allow the collection of an enormous amount of customer data. Profiles based on this data enable an improved estimation of the electricity demand and ability to pay of future customers. By applying these digital solutions to site identification and pre-feasibility assessments, project development and planning can become considerably more lean and efficient.

Operation and maintenance

Once the mini-grid system is installed, it enters the technical operation phase. The key challenge here is to keep the operation and maintenance costs low. Remote monitoring systems (RMS), often cloud-based and connected via telecommunication link with the grid's SCADA system, allow for a real-time, remote observation of critical system parameters such as battery status or the performance of the generation system. For so-called predictive maintenance, algorithms can anticipate faults and notify service personnel to perform maintenance duties if needed. Providers of RMS technologies – for example the US supplier Powerhive [58] or AMPP from the Netherlands [77] – claim that the frequency of component replacements as well as logistics and labour costs can be significantly reduced [78].

In the context of Sub-Saharan Africa, these opportunities for cost reduction particularly relate to the reduction of long and costly trips to mini-grid sites, the avoidance of system failures and the extension of the life span of the system's components [71,79–81]. Whether remote monitoring can actually reduce the number of staff employed for the on-site maintenance of the system is questionable [56,73,80]. RMS could serve as a support tool for local technicians, which still play an important role for the relationship between the operator and the local customers [73]. It may, however, be necessary to provide additional training to enhance the skills of the local technical staff to keep up with the complexity of the system [73]. Since today there is already often a lack of skilled personnel on the ground [82], this could become a challenge for the digitalisation of mini-grids in the future.

Customer management

An important task for mini-grid operators is to ensure the cash-flow, i.e. collect the payments from the customers. Depending on the socio-economic context and the chosen payment approach, e.g. fee-for-service or pay-as-you-go, a number of ICT-assisted payment schemes are available. Especially in East Africa, where mobile money, such as M-Pesa in Kenya, is a widespread means of payment, these schemes enjoy high popularity. Companies like M-Kopa [83] or Angaza [84] run their business model on mobile payment schemes. Here, customers are reminded remotely of the payment deadlines and in case of discontinued payments, the control box (or the smart meter) automatically disconnects the household from the mini-grid.

Other approaches include the sales of "pre-paid" scratchcards which contain an SMS code with which the customers can remotely activate their electricity supply. This approach is for example used by Azuri Technologies [85]). With the proliferation of smartphones and tablets new and more sophisticated ways of organising remote customer relationships become possible. Mobile apps, could for instance, inform customers more precisely about their payments, system status and energy consumption patterns, and could allow them to interact directly with the energy service company. Specialised apps, developed exclusively for service companies, could provide on-site staff members with remote access to (cloud-based) system data and guide them through service operations. It goes without saying that all these approaches only work in areas with a good mobile (data) network coverage. This may be one reason why currently the pos-

Deep read: In early 2019, the Fondazione Eni Enrico Mattei (FEEM) published a study on "Digitalization for Energy Access in Sub-Saharan Africa: Challenges, Opportunities and Potential Business Models" [43]. The study provides a comprehensive overview as well as an in-depth analysis of the strengths and weaknesses of pay-as-you-go business models in the off-grid solar sector, including practical examples and recommendations for policy-makers.

Mazzoni, D. 2019. Digitalization for Energy Access in Sub-Saharan Africa. Challenges, Opportunities and Potential Business Models. FEEM Working Paper No. 2 2019.

sibilities of smart customer management are exploited to a rather limited extent in the context of Sub-Saharan Africa. It has been observed that even mini-grids that have been built over the past five years use over-the-counter voucher payment systems despite the possibility of mobile money [72].

Furthermore, smart meters could enable the use of post-paid systems. However, the success of such a post-paid system depends highly on the relationship with the respective community [56]. While having an internet connection would be a favourable condition for smart meters and post-paid systems, it could even work if the smart meters are not constantly connected to the internet. Companies have developed solutions for smart meters to store electricity consumption data. This data could then be uploaded as soon as the internet connection is again available [56].

However, more sophisticated systems for customer management, for instance smart meters with displays, may increase costs for the customers. A further aspect concerns cyber security and data protection. Mini-grids and rural customers are certainly not a typical target of cyber-crime. However, these issues should be properly addressed by the technology developers.

Finally, more recent attempts in the mini-grid community include the exploration of alternative approaches towards customer relationships by moving away from the traditional "supplier-consumer" model towards a "prosumer" model. In this model, grid-connected customers themselves become (partly) producers of electricity, for instance by operating their own photovoltaic modules on their home. Excess electricity that is not self-consumed can be traded across the mini-grid to neighbours. For the billing, electricity exchanges need to be measured accurately with bi-directional smart meters. The company SOLshare [86], based in Bangladesh, has developed a peer-to-peer solar energy trading platform based on distributed ledger technology ("blockchain") for such community mini-grids. As the SOLshare concept is relatively recent and one of the first of its kind, it is recommended to observe and assess its experiences carefully to identify lessons-learned that could be useful for similar approaches in Sub-Saharan Africa.

5.5 Mini-grids to power digital technologies for productive use

Productive uses of energy are essential for the creation of value and employment in off-grid communities. However, they do not automatically result from energy access. Indeed, productive uses require a complex interaction of different factors which include among others direct engagement with the respective community, sensitisation, education, training as well as the availability of micro-finance solutions [71–73]. Usually, views on the potential of productive use devices in rural areas have centred on benefits for agricultural activities and food production (e.g. grain mills, water pumps or milk cooling) or local commerce and manufacturing such as sewing. Communication and information services, however, play an increasingly important role in developing economic activities in rural areas. In recent years, a number of (social) businesses have emerged combining energy access with access to internet and mobile communication, e.g. in internet cafés, tele-kiosks or via WIFI hotspots. For example, Africa Greentech [87] and Winch Energy [88] have developed solar internet kiosks that provide not only clean electricity from a photovoltaic system, but also satellite-based internet access. Similarly, due to the increasing prevalence of digital technologies, it is likely that productive use is more and more shifted towards services which could complement or even improve conventional productive use approaches. For example, e-scooters charged by the mini-grid could offer transportation services in rural areas via an online platform and even include cooling boxes to keep food products fresh or medications and vaccines cool. In the agricultural sector, tools and other assets could also be shared via platforms.

Still, access to mobile technologies alone may not suffice to create sustainable benefits. The lack of training and skills as well as adequate content and information on the internet is still a major barrier hindering the use of digital technologies, in particular in rural areas. In order to tackle this challenge, some companies have started to provide e-learning solutions to improve the take-up of productive uses (see Box 8). Such approaches, if well-planned and targeted, could also contribute to closing the gender divide in the productive use of energy.

Finally, mini-grids can be used to power mobile phone antenna in isolated villages. Connected to mini-grids, they could provide a double benefit: First, they improve telecommunication coverage in the region. Second, they could become a catalyst for the construction of the mini-grid itself which, without the investment of a mobile phone operator, may not be possible. As an example, in India, OMC Power has used this anchor load model displacing diesel-based power supply to telecom towers with renewable energy while enhancing electricity access to neighbouring areas [90]. In Sub-Saharan Africa, however, this model is so far less prevalent [72,73]. One reason is that rural communities are often very scattered. Furthermore, energy access and telecommunication companies often have different interests and rarely cooperate. Still, much could be learned from experiences in other countries such as India.

Box 8: Linking energy access with education

Education and access to electricity go hand in hand in order to improve livelihoods for rural populations. REI-Cameroon (REIc), a solar mini-grid company, has built on this idea to develop a digital education platform for communities powered by mini-grids [89]. This platform serves adults and youths with audio-visual content providing basic literacy and skill development in vocational trades such as tailoring, woodwork, welding, hair dressing, etc. The platform uses the mini-grid network infrastructure to provide hotspots where the students connect and study using mobile phones, tablets or laptops.

© REI-Cameroon

6. Conclusions

Mini-grids are an important instrument to achieve SDG7, 9 and 13 in Sub-Saharan Africa and globally. Digital technologies provide numerous opportunities in the mini-grid sector by for instance providing new funding opportunities, improving the functioning of mini-grids as well as optimising maintenance and customer management. With mini-grids ensuring access to electricity, digital technologies could be used to advance productive uses, be it through the use of digital appliances, access to information and learning platforms or the development of new services linked to digital technologies. On the other hand, the use of digital technologies in mini-grids in rural Sub-Saharan Africa poses new challenges and risks, in particular with regard to privacy and data security. Coming back to the requirements for sustainable mini-grids outlined in Chapter 4, the following conclusions can be drawn concerning the potentials of digital technologies to achieve these requirements (see Annex III):

1) **Mini-grids should be powered by renewable energy sources.** The application of digital technologies enables mini-grids to better cope with complexity challenges that go along with the integration of intermittent renewable energy sources. For example, smart management of generation, storage and demand of electricity can improve the balance and efficiency of mini-grids based on renewable energy sources. In addition, digital technologies allow for the integration of additional information – such as weather forecasts – to develop optimal load schedules for renewable mini-grids. Furthermore, digital tools for the planning and design of mini-grids could support the identification of sites that are optimal for the use of renewable energy sources.

2) **Mini-grids should account for the specific socio-economic context.** Digital planning and design tools can complement conventional modes of design and planning and help to integrate relevant information, such as locations of households, businesses, community centres and existing infrastructures. In this way, the specific characteristics of a certain location could be better accounted for. If in the future data on the development of load profiles of communities is made available, this data could be used to improve forecasts about future electricity demand and thus contribute to a more adequate sizing of mini-grids. Furthermore, tools for remote maintenance and support can help to provide better services to remote communities, decrease downtimes and the time need for repairs. Finally, digital technologies already today provide solutions for customer information and payment, e.g. though mobile payment apps, which could further develop. An appropriate and user-centred design of these technologies is imperative in this regard.

3) **Mini-grids should enable equitable and affordable electricity costs.** Starting with the planning phase, digital technologies, big data and improved planning tools can reduce the initial costs of project development and mini-grid systems. The intelligent management and operation of mini-grids through digital technologies could further contribute to reducing electricity costs. Besides, this could allow flexible prices that may decrease the average electricity costs for all users.

4) **Mini-grids should provide reliable electricity supply.** Digital technologies can improve proper demand estimation and sizing of mini-grids which already increases their reliability. In addition, remote maintenance and control will help to reduce downtimes of the system. Smart demand side management could prevent power outages, e.g. by partially reducing demand in cases of low battery charging status.

5) **Mini-grids should be oriented towards productive uses.** Digital tools can help to better integrate potential productive uses into the planning and design of mini-grids. Furthermore, they can be used to improve conventional equipment for productive uses, such as irrigation systems for agriculture. Besides, linking mini-grids and access to modern ICTs could add to the creation of an enabling environment for new economic activities such as digital services (e.g. scanning official documents, internet cafés, telephone charging).

6) **Mini-grids should adapt to new conditions.** Digital technologies, in particular smart meters, could facilitate the setup of more decentralised mini-grid configurations, for instance by enabling consumers to partially become producers ("prosumers") of electricity and possibly even exchanging it with other prosumers on digital peer-to-peer electricity trading platforms. Digitalisation could furthermore contribute to a flexible expansion of the mini-grid when demand increases at a later point of time and allow its connection to the main grid.

7) **Mini-grids should account for transparency and consumer protection.** Digital technologies in mini-grids collect data that are used to improve the efficiency and reliability of the system. However, if data security and privacy issues are not carefully handled this may bear the risk of negative consequences for the consumer. A responsible and transparent data handling is therefore paramount. Digital tools can bring transparency to the users about which data is being collected and subsequently empower them as consumers. To serve these purposes, an appropriate and user-centred design of the technologies is essential, in particular in rural contexts where illiteracy is often a challenge.

8) **Mini-grids should minimise their ecological footprint.** Smart management of mini-grids can increase the life-span of essential components like batteries, which are not only the most expensive parts of the system, but also have a high ecological footprint. Predictive maintenance helps to anticipate components' failure even before it occurs which avoids larger damage to the system and may reduce the production of e-waste. At the same time, digital technologies could be used to keep track of mini-grid components to ensure their proper decommissioning, disposal or recycling.

Many of the potentials that could unfold through the integrated use of digital technologies in and for mini-grids in Sub-Saharan Africa have not yet been tapped into. Technical issues, even internet access, do not appear to be limiting factors for the application of digital technologies in mini-grids. As this study has shown, regulatory, economic and socio-cultural framework conditions play a much more decisive role. These factors should be carefully considered and so should the potentially adverse consequences of ICT use. The integration of digital technologies into mini-grids should never be an end in itself, but always serve the needs of the people being provided with electricity services.

7. Options for action

Following these conclusions, there are several options for key stakeholders in order to foster the creation of a positive and sustainable nexus of mini-grids and digital technologies:

Policy-makers could contribute by ...

- Providing a long-term plan for grid extension so that mini-grid stakeholders are better able to evaluate to which extent digital technologies should be incorporated in the mini-grid.
- Developing regulatory frameworks that allow flexible tariffs for operators of the mini-grid so that digital solutions such as smart meters become attractive, for instance through managing demand as a function of variable, time-dependent tariffs.
- Providing regulation that is technology-neutral and fosters the development of best practices.
- Providing incentives and subsidies for high-costs and high-risk projects that could serve the development and testing of digital solutions for the improvement of mini-grids.
- Supporting the development of standards and quality criteria for digital technologies in mini-grids.
- Providing a framework for data security and consumer protection, while on the other hand encouraging the sharing of non-personal data to improve demand forecasts for mini-grids.
- Engaging in an open dialogue with innovators to develop suitable framework conditions addressing their needs.
- Fostering research and innovation at the intersection of energy access and productive uses.

Donor organisations could contribute by ...

- Incentivising or even requiring that data from the mini-grids they funded is shared on an accessible and open platform.
- Supporting technology transfer and cooperation.
- Including technical requirements for appropriate digital features in mini-grid tenders that best serve the local context and needs and foster user-centric designs of technologies.
- Fostering collaboration between communities, innovators and local researchers to develop tailored solutions for specific local contexts.
- Assessing the implications of digital technologies in mini-grids in order to create solid knowledge about their effects, for instance on costs, long-term sustainability as well as consumer satisfaction and the creation of productive uses.

Companies and technology developers could contribute by …

- Putting consumer needs at the centre of technology development and considering specific local contexts and requirements.
- Sharing their data and using open-source software.
- Jointly developing standards and building technologies that – based on these standards – is compatible and allows for more flexibility and possible extensions.
- Engaging and exchanging with other companies and innovators to create knowledge networks and to share lessons-learned from success stories as well as failures.
- Offering capacity-building measures which empower local communities to understand the technology and take on repair and maintenance responsibilities themselves.

Moreover, policy-makers, donor organisations and technology developers should collaborate and exchange with each other as well as other stakeholders in order to create favourable framework conditions and new impetus for a purposeful use of digital technologies for sustainable mini-grids.

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Annex I: Overview and profiles of selected Sub-Saharan African countries

Socio-economic indicators	Ethiopia	Kenya	Madagascar	Mali	Mozambique	Nigeria	Senegal	Tanzania	Uganda	Zambia
Population (in millions, 2018) [a]	109.2	51.4	26.3	19.1	29.5	195.9	15.9	56.3	42.7	17.4
Rural population (in %, 2018) [a]	79	73	63	58	64	50	53	66	76	56
Rural population with access to electricity (in %, 2016) [b]	29.2	59.7	6.9	6.4	14.7	34.1	43.5	17.1	18.6	6.5
Individuals using the internet (in %, 2017) [c]	18.6	17.8	9.8	12.7	20.8	27.7	29.6	16	23.7	27.9
Unique mobile subscriptions (in millions, 2017) [d]	34.7	28.3	5.9	11.4	13.8	86	8.4	23.7	17	9
Rural population with mobile money account (in %, 2017) [a]	0.3	72.6	9.9	20.6	18.2	2.6	28.1	37.8	50.1	25.5

Table A: Overview of selected socio-economic indicators

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.
c) ITU, World Telecommunication/ICT Development Report and database.
d) GSMA. The Mobile Economy. Sub-Saharan Africa 2017.

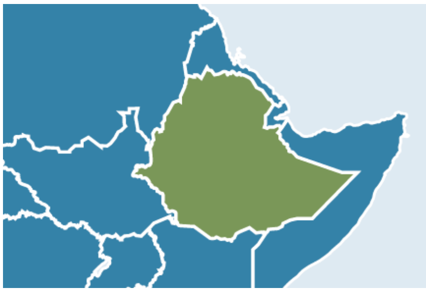
Mini-grid regulation – selected indicators	Ethiopia	Kenya	Madagascar	Mali	Mozambique	Nigeria	Senegal	Tanzania	Uganda	Zambia
Programs to support the development of mini-grids exist	✔	✔	✘	✔	✘	✔	✔	✔	✔	✔
Regulation clarifies what will occur when main grid reaches the mini-grid	✔	✔	✔	✘	✘	✔	✘	✘	✘	✘
Mini-grids can be owned and operated by private operators	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Operators are allowed to charge a tariff different from the national tariff	✔	✔	✘	✔	✔	✔	✘	✔	✔	✔
Publicly funded mechanisms exist to secure viability gap funding	✔	✔	✘	✔	✘	✘	✘	✔	✔	✘
Duty exemptions and/or subsidies for mini-grids exist	✔	✔	✔	✔	✘	✘	✘	✔	✔	✔
Technical standards exist detailing requirements for mini-grids to connect to the grid	✘	✔	✔	✔	✘	✔	✘	✔	✘	✘
Environmental regulation on the disposal of solar devices exists	✘	✔	✘	✘	✘	✘	✔	✘	✘	✔

Table B: Overview of selected RISE indicators

Sources:
World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/ (last checked 10 July 2019).

ETHIOPIA

Located in the Horn of Africa, Ethiopia has one of the largest populations in Sub-Saharan Africa. The country's economy is mainly dependent on the agricultural sector for income generation and job creation. Economically, Ethiopia is one of the least developed countries in the world with a large majority of Ethiopians living in rural areas. Here – in contrast to Ethiopia's urban centres – access to electricity remains a major challenge despite abundant solar, wind and hydropower resources.



109.2 Mio. people (2018) a)

79 % live in rural areas (2018) a)

29.2 % of rural population with access to electricity (2016) b)

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Indicator	
Programs to support the development of mini-grids exist	✔
Regulation clarifies what will occur when main grid reaches the mini-grid	✔
Mini-grids can be owned and operated by private operators	✔
Operators are allowed to charge a tariff different from the national tariff	✔
Publicly funded mechanisms exist to secure viability gap funding	✔
Duty exemptions and/or subsidies for mini-grids exist	✔
Technical standards exist detailing requirements for mini-grids to connect to the grid	✘
Environmental regulation on the disposal of solar devices exists	✘

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

Under Ethiopia's 2017 National Electrification Programme, the government aims to achieve universal electrification by 2025 [1]. The plan envisages that 65 percent of the population will be served by the main grid and 35 percent through off-grid infrastructures such as mini-grids and solar stand-alone systems. Considering the planned network extensions up to 2020, it is estimated that 13 million people in Ethiopia would be best served by mini-grids [2]. To foster mini-grid development and private sector involvement, legislative framework conditions have been substantially improved. However, there still remains a lack of planning capacity and experience in the off-grid sector which hampers mini-grid expansion [2].

ICT adoption & digital development

Ethiopia's telecommunication sector has long been dominated by a state-owned operator. In turn, this has led to a lack of innovation, high prices for consumers, low adoption rates of modern information and communication technologies (ICTs) and substantial obstacles in the development of private enterprises in the sector [3]. However, the government aims to liberalise the telecommunication sector and to provide a new regulatory framework including among others the protection of consumer rights [3]. Furthermore, it has devoted substantial resources to infrastructural improvements in order to facilitate access in rural areas [4].

18.6 % of individuals use the internet (2017) a)

34.7 Mio. unique mobile subscriptions (2017) b)

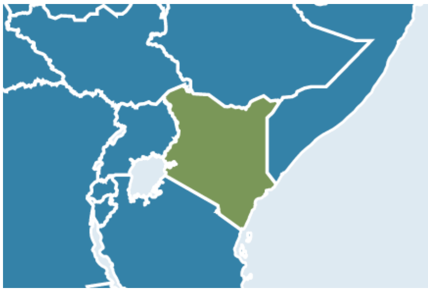
0.3 % of rural population with mobile money account (2017) c)

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:
[1] World Bank. 2018. Ethiopia's Transformational Approach to Universal Electrification. https://www.worldbank.org/en/news/feature/2018/03/08/ethiopias-transformational-approach-to-universal-electrification (Accessed 01 July 2019).
[2] SE4All Africa Hub, African Development Bank. 2017. Mini Grid Market Opportunity Assessment: Ethiopia. https://www.powerforall.org/application/files/2915/5118/9654/Ethiopia3.pdf (Accessed 01 July 2019).
[3] Fukui, Roku. 2019. In Ethiopia, digital development just took a major leap forward. https://blogs.worldbank.org/digital-development/ethiopia-digital-development-just-took-major-leap-forward (Accessed 01 July 2019).
[4] ITU. 2018. Measuring the Information Society Report 2018 – Volume 2. https://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2018/MISR-2018-Vol-2-E.pdf (Accessed 02 July 2019).

KENYA

Kenya is one of the fastest growing and most diversified economies in Sub-Saharan Africa with a vibrant private sector and a well-educated and skilled workforce. The country has made significant progress in infrastructure as well as in social and economic development over the past decade. Still, poverty – especially in rural areas – remains a major challenge. Providing electricity from renewable energy sources is therefore central for poverty reduction and rural development in Kenya.



51.4 Mio. people (2018) a)

73 % live in rural areas (2017) a)

59.7 % of rural population with access to electricity (2016) b)

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Programs to support the development of mini-grids exist	✔
Regulation clarifies what will occur when main grid reaches the mini-grid	✔
Mini-grids can be owned and operated by private operators	✔
Operators are allowed to charge a tariff different from the national tariff	✔
Publicly funded mechanisms exist to secure viability gap funding	✔
Duty exemptions and/or subsidies for mini-grids exist	✔
Technical standards exist detailing requirements for mini-grids to connect to the grid	✔
Environmental regulation on the disposal of solar devices exists	✔

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

Kenya aims to achieve universal electrification by 2022. Through its Last Mile Connectivity Program (LMCP), the government aims to connect all people living within 600m of a transformer to the central grid [1]. Still, mini-grids could play a significant role in providing electricity access to rural communities. While it is estimated that by 2017 at least 65 mini-grids operated in Kenya, their number could grow to 2,000-3,000 by 2021 if favourable regulations are put in place [2]. Although provisions and regulations for mini-grids have been developed, private actors are often deterred by the inflexible tariff model, uncertainty about when the main grid arrives, as well as limited opportunities to receive subsidies and public grants for off-grid projects.

ICT adoption & digital development

Kenya is a leading country in the adoption of modern information and communication technologies (ICTs) and mobile money in Sub-Saharan Africa. Since the early 2000s, the Kenyan government has utilised the internet as a tool for development and increased its efforts to provide adequate infrastructures [3]. With the "Digital Economy Blueprint" launched in May 2019, Kenya aims to provide a comprehensive framework for the development of the ICT sector [4]. Still, challenges remain with regard to internet access in rural areas, high costs of equipment and the lack of relevant online content [3].

17.8 % of individuals use the internet (2017) a)

28.3 Mio. unique mobile subscriptions (2017) b)

72.6 % of rural population with mobile money account (2017) c)

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:

[1] World Bank. 2017. Mini-Grids in Kenya. A Case Study of a Market at a Turning Point. Energy Sector Management Assistance Program (ESMAP). Washington, D.C., USA.

[2] Duby, S. and Engelmeier, T. 2017. Kenya: The World's Microgrid Lab. https://www.tfeconsulting.com/_website/wp-content/uploads/2017/12/TFE_Report-Kenya-new.pdf (Accessed 22 June 2019).

[3] Mureithi, M. 2017. The Internet Journey for Kenya: The Interplay of Disruptive Innovation and Entrepreneurship in Fueling Rapid Growth. In: Ndemo, B.; Weiss, T. (eds). Digital Kenya. Palgrave Studies of Entrepreneurship in Africa.

[4] Government of Kenya. 2019. Digital Economy Blueprint. Powering Kenya's Transformation. http://www.ict.go.ke/wp-content/uploads/2019/05/Kenya-Digital-Economy-2019.pdf (Accessed 02 July 2019).

MADAGASCAR

The island state Madagascar, located in the Indian Ocean east of Mozambique, is one of the poorest countries in the world. The agricultural sector forms the backbone of Madagascar's economy and provides both employment and livelihoods for the vast majority of its population. Despite economic growth, especially in the service sector, poverty remains a major challenge as agricultural productivity is low. Rural electrification therefore plays an important role in improving living conditions and income opportunities.

26.3 Mio. people (2018) a)

63% live in rural areas (2018) a)

6.9% of rural population with access to electricity (2016) b)

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Indicator	
Programs to support the development of mini-grids exist	✘
Regulation clarifies what will occur when main grid reaches the mini-grid	✔
Mini-grids can be owned and operated by private operators	✔
Operators are allowed to charge a tariff different from the national tariff	✘
Publicly funded mechanisms exist to secure viability gap funding	✘
Duty exemptions and/or subsidies for mini-grids exist	✔
Technical standards exist detailing requirements for mini-grids to connect to the grid	✔
Environmental regulation on the disposal of solar devices exists	✘

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

Madagascar's New Energy Policy (NEP), published in 2015, aims to provide access to modern electricity services to 70% of its population by 2030, mainly through grid-extension, mini-grids as well as other off-grid technologies [1]. Currently, many rural communities without access to the main grid depend on – mostly diesel-powered – mini-grids [2]. This provides the opportunity to hybridise these mini-grids through solar photovoltaics [1]. Solar power, in particular photovoltaic, is currently mainly used to deliver electricity to public buildings such as health clinics and for single households in rural areas [2, 3]. According to the NEP, solar mini-grids are projected to serve one percent of households with electricity by 2030 [1].

ICT adoption & digital development

Madagascar aims to exploit the opportunities of modern information and communication technologies (ICTs) in order to spur its economy and to reduce poverty. The government has launched several projects to develop infrastructures and foster ICT adoption, for instance by improving the coverage of underserved regions and promoting the use of computers and tablets in schools and other educational institutions [4]. Still, the country struggles with major challenges such as affordability of and access to modern ICTs and a large rural-urban divide.

9.8% of individuals use the internet (2017) a)

5.9 Mio. unique mobile subscriptions (2017) b)

9.9% of rural population with mobile money account (2017) c)

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:

[1] Pigaht, M.; Werler, S. 2016. Madagascar: Opportunities for Solar Business. Federal Ministry for Economic Affairs and Energy (BMWi): Berlin. http://ader.mg/pdf_files/infos/Energies_Renouvelables/Solaire/PDP_Report_Solar_Madagascar.pdf (Accessed 02 July 2019).

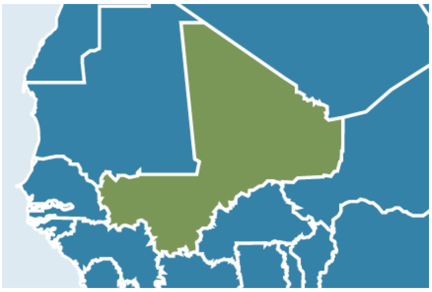
[2] Energypedia. Madagascar Energy Situation. https://energypedia.info/wiki/Madagascar_Energy_Situation (Accessed 02 July 2019).

[3] Ministry of Energy. (Undated). Expression of Interest to participate in the Scaling Up Renewable Energy In Low Income Countries Program (SREP). Antananarivo: Ministry of Energy.

[4] ITU. 2018. Measuring the Information Society Report 2018 – Volume 2. https://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2018/MISR-2018-Vol-2-E.pdf (Accessed 02 July 2019).

MALI

Mali is a vast, landlocked country in West Africa and one of the poorest countries in the world. Whereas the economy is growing – the agricultural and service sectors being the most important drivers of this growth – it is still hampered by a lack of diversification. Instability and conflicts hamper social and economic development. In addition, high population growth and vulnerability towards droughts and climate change effects challenge food security and livelihoods especially in rural areas where most of Mali's most vulnerable populations live.



19.1 Mio. people (2018)[a)]

58 % live in rural areas (2018)[a)]

6.4 % of rural population with access to electricity (2016)[b)]

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Programs to support the development of mini-grids exist	✔
Regulation clarifies what will occur when main grid reaches the mini-grid	✘
Mini-grids can be owned and operated by private operators	✔
Operators are allowed to charge a tariff different from the national tariff	✔
Publicly funded mechanisms exist to secure viability gap funding	✔
Duty exemptions and/or subsidies for mini-grids exist	✔
Technical standards exist detailing requirements for mini-grids to connect to the grid	✔
Environmental regulation on the disposal of solar devices exists	✘

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

Mali depends largely on imported fossil fuels and to a lesser extent on hydropower for electricity production, leaving much of its renewable energy potentials untapped [1]. Given the vast size of the country and its dispersed settlements especially in the rural North, grid extension is a too costly option to promote electricity access [2]. In rural areas, electricity is therefore often provided by diesel generators, but solar solutions are slowly catching up [2]. In recent years, the government has promoted the installation of photovoltaic (PV) and hybrid diesel-PV mini-grids to improve clean electricity services in rural areas. A 2016 survey revealed that by that time, 13 PV-, 13 biodiesel and 45 PV-hybrid mini-grids (out of a total of 73) were installed [3].

ICT adoption & digital development

The government of Mali has identified modern information and communication technologies (ICTs) as important tools for social and economic development and managed to achieve a high level of basic telecommunication access [4]. The national strategy for the development of the digital economy, called "Digital Mali 2020", aims at improving telecommunication infrastructures, developing relevant online contents, expanding digital services and developing human capacities as well as a vibrant digital industry [5].

12.7 % of individuals use the internet (2017)[a)]

11.4 Mio. unique mobile subscriptions (2017)[b)]

20.6 % of rural population with mobile money account (2017)[c)]

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:

[1] UNEP. 2017. Atlas of Africa Energy Resources. https://wedocs.unep.org/bitstream/handle/20.500.11822/20476/Atlas_Africa_Energy_Resources.pdf (Accessed 02 July 2019).

[2] Energypedia. Mali Energy Situation. https://energypedia.info/wiki/Mali_Energy_Situation (Accessed 02 July 2019).

[3] Hobson, Eseoghene Larkwei. 2016. Mapping & assessment of clean energy mini-grid experiences in West Africa. ECOWAS Centre for Renewable Energy and Energy Efficiency. http://www.ecreee.org/sites/default/files/mapping_and_assessment_of_existing_clean_energy_mini-grid_experiences_in_west_africa_ecreee.pdf (Accessed 03 July 2019).

[4] ITU. 2018. Measuring the Information Society Report 2018 – Volume 2. https://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2018/MISR-2018-Vol-2-E.pdf (Accessed 02 July 2019).

[5] Ministry of Digital Economy, Information and Communication. Undated. Mali Numérique 2020. Stratégie Nationale de Développement de l'Economie Numérique. Draft. http://138.68.77.244/wp-content/uploads/2018/03/MALI-Nume%CC%81rique-2020.pdf

MOZAMBIQUE

Mozambique is located in East Africa on the shore of the Indian Ocean. Its 2,500 kilometres of coastline make it particularly vulnerable to tsunamis and cyclones which hit the country hard in the recent past. The country's economy lacks diversification and is only growing slowly. Subsistence agriculture provides livelihoods to many people in rural areas where poverty remains a major challenge.

29.5 Mio. people (2018) [a)]

64 % live in rural areas (2018) [a)]

14.7 % of rural population with access to electricity (2016) [b)]

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Programs to support the development of mini-grids exist	✗
Regulation clarifies what will occur when main grid reaches the mini-grid	✗
Mini-grids can be owned and operated by private operators	✓
Operators are allowed to charge a tariff different from the national tariff	✓
Publicly funded mechanisms exist to secure viability gap funding	✗
Duty exemptions and/or subsidies for mini-grids exist	✗
Technical standards exist detailing requirements for mini-grids to connect to the grid	✗
Environmental regulation on the disposal of solar devices exists	✗

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

Mozambique aims to achieve 100 percent electricity access by 2030 with off-grid solar power offering a cost-effective solution to complement grid extension in remote and sparsely populated rural areas [1]. The solar potentials of Mozambique are currently largely untapped and only used for the electrification of rural areas through off-grid solutions [2]. Due to a lack of favourable and clear regulation, the mini-grid sector has so far not gained traction and private sector participation is rather low. Currently, there are only a few mini-grids installed, most of which are diesel-powered and face challenges with regard to operation and maintenance [1]. According to a 2017 report, it is estimated that 5.6 million people in Mozambique would be best served by mini-grids [3].

ICT adoption & digital development

In recent years, infrastructure development and increasing competition in the telecommunication market have lowered prices and improved access to modern telecommunication services [4]. Still, Mozambique has a long way to go to fully benefit from modern information and communication technologies (ICTs) [5]. For a large part of the population, devices and a high-speed, reliable internet connection remain unaffordable while at the same time there is a lack of digital skills and relevant online content in local languages hampering ICT adoption and the development of beneficial network effects [5].

20.8 % of individuals use the internet (2017) [a)]

13.8 Mio. unique mobile subscriptions (2017) [b)]

18.2 % of rural population with mobile money account (2017) [c)]

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:

[1] Baruah, P.; Coleman, B. 2019. Country Brief: Mozambique: Off-grid solar power in Mozambique: Opportunities for universal energy access and barriers to private sector participation. Global Green Growth Institute. https://gggi.org/site/assets/uploads/2019/02/20190218_-Country-Brief_Mozambique.pdf (Accessed 03 July 2019).

[2] UNEP. 2017. Atlas of Africa Energy Resources. https://wedocs.unep.org/bitstream/handle/20.500.11822/20476/Atlas_Africa_Energy_Resources.pdf (Accessed 03 July 2019).

[3] SEforALL Africa Hub; African Development Bank. 2017. Mini Grid Market Opportunity Assessment: Mozambique. https://greenmini-grid.se4all-africa.org/sites/default/files/GMG%20MDP%20Document%20Series%20%235%20Mozambique%20Assessment%2003-05-17.pdf (Accessed 03 July 2019).

[4] ITU. 2018. Measuring the Information Society Report 2018 – Volume 2. https://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2018/MISR-2018-Vol-2-E.pdf (Accessed 02 July 2019).

[5] Gillwald, Alison; Mothobi, Onkokame; Rademan, Broc. 2019. The state of ICT in Mozambique 2018. RIA Policy Paper. https://researchictafrica.net/wp/wp-content/uploads/2019/03/2019_After-Access_The_State-of-ICT-in-Mozambique.pdf (Accessed 03 July 2019).

NIGERIA

Nigeria is the most populous country on the African continent and has one of the youngest populations worldwide. The economy is largely dependent on fossil fuel resources and remains weak due to a lack of diversification and a challenging business environment. Rapid urbanisation has caused numerous problems as the development of infrastructures, housing and the provision of health and education services can hardly keep up. Poverty remains a major challenge in both rural and urban areas.

195.9 Mio. people (2018)[a]

50 % live in rural areas (2018)[a]

34.1 % of rural population with access to electricity (2016)[b]

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Programs to support the development of mini-grids exist	✓
Regulation clarifies what will occur when main grid reaches the mini-grid	✓
Mini-grids can be owned and operated by private operators	✓
Operators are allowed to charge a tariff different from the national tariff	✓
Publicly funded mechanisms exist to secure viability gap funding	✗
Duty exemptions and/or subsidies for mini-grids exist	✗
Technical standards exist detailing requirements for mini-grids to connect to the grid	✓
Environmental regulation on the disposal of solar devices exists	✗

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

Due to poor maintenance and frequent failures, the Nigerian main grid only serves 23 percent of the population, despite having been expanded significantly in past decades [1]. The potential for electrification through mini-grids is high. Until recently, mini-grids played only a marginal role in supplying electricity to unserved populations. A 2018 study suggests that approximately 30 solar mini-grids serving 6,000 customers are in operation [2]. However, in 2017 Nigeria issued favourable legislation for mini-grids that is expected to boost the development of the sector. Furthermore, in May 2019, the private sector led mini-grid and solar home components of the Nigeria Electrification Project were launched which aim to provide electricity to 300,000 households and 30,000 enterprises in rural areas by 2023 [3].

ICT adoption & digital development

The Nigerian government is determined to put modern information and communication technologies (ICTs) to work for socio-economic development. The country has a vibrant startup community, a competitive ICT market and issued favourable regulatory strategies for the development of the sector [4]. Still, major challenges remain with regard to universal access to and affordability of modern telecommunication services – one major issue the government aims to tackle with the Nigeria ICT Roadmap 2017 – 2020 [5].

27.7 % of individuals use the internet (2017)[a]

86 Mio. unique mobile subscriptions (2017)[b]

2.6 % of rural population with mobile money account (2017)[c]

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:

[1] World Bank. 2017. Mini Grids in Nigeria. A Case Study of a Promising Market. Energy Sector Management Assistance Program (ESMAP). https://openknowledge.worldbank.org/bitstream/handle/10986/29016/121827-ESM-dNigeriaMiniGridsCaseStudyConfEd-PUBLIC.pdf?sequence=1&isAllowed=y (Accessed 03 July 2019).

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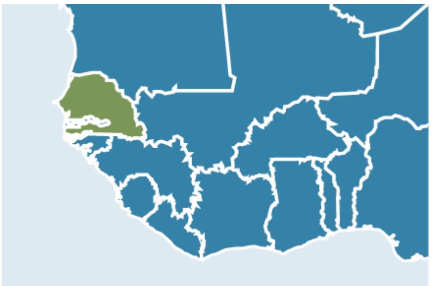
SENEGAL

Located in West Africa at the shore of the Atlantic Ocean, politically Senegal is one of the most stable countries in Africa. The country has shown good growth rates over the past years and has a more diversified economy than many other Sub-Saharan African countries. Still, poverty affects a large share of the population. Livelihoods in rural areas largely depend on rain-fed subsistence farming which is highly vulnerable towards climate change.



15.9 Mio. people (2018) [a]

53 % live in rural areas (2018) [a]

43.5 % of rural population with access to electricity (2016) [b]

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Programs to support the development of mini-grids exist	✓
Regulation clarifies what will occur when main grid reaches the mini-grid	✗
Mini-grids can be owned and operated by private operators	✓
Operators are allowed to charge a tariff different from the national tariff	✗
Publicly funded mechanisms exist to secure viability gap funding	✗
Duty exemptions and/or subsidies for mini-grids exist	✗
Technical standards exist detailing requirements for mini-grids to connect to the grid	✗
Environmental regulation on the disposal of solar devices exists	✓

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

The Senegalese government aims to provide electricity coverage to at least 90% of rural households by 2025 [1]. Grid extension is very costly especially in sparsely populated remote areas. Mini-grids are therefore already widely deployed in Senegal. With an estimated 142 clean energy mini-grids, it is one of the leading countries in West Africa [2]. Mini-grids are supported by the availability of subsidies and rural development funds and typically deployed through public-private partnerships where the government owns the grid infrastructure which is then operated by private actors [3]. However, challenges for mini-grids remain especially with regard to low consumption and purchasing power of consumers as well as lengthy administrative processes [4].

ICT adoption & digital development

In recent years, the Senegalese government has taken important steps to leverage modern information and communication technologies (ICTs) as a means for socio-economic development. The Strategy Digital Senegal 2016-2025 seeks to expand broadband and to provide infrastructures in unserved areas [5]. The strategy furthermore aims to improve the ecosystem and regulative framework for innovative private businesses in the ICT sector, strengthen ICT skills and education as well as improve administrative capacities.

29.6 % of individuals use the internet (2017) [a]

8.4 Mio. unique mobile subscriptions (2017) [b]

28.1 % of rural population with mobile money account (2017) [c]

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:

[1] SE4All Africa Hub. Undated. Senegal. https://www.se4all-africa.org/seforall-in-africa/country-data/senegal/ (Accessed 04 July 2019).

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TANZANIA

Over the past decade, Tanzania has posted relatively high growth rates. Agriculture still plays a dominant role in income generation and the creation of jobs, with rural populations largely dependent on subsistence farming. However, mining, tourism and the industrial sector have gained in importance. Poverty remains a major challenge for the country, with a lack of housing, education and health services as well as adequate infrastructures being the main obstacles for poverty reduction.

56.3 Mio. people (2018)[a)]

66 % live in rural areas (2018)[a)]

17.1 % of rural population with access to electricity (2016)[b)]

Sources:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Programs to support the development of mini-grids exist	✔
Regulation clarifies what will occur when main grid reaches the mini-grid	✘
Mini-grids can be owned and operated by private operators	✔
Operators are allowed to charge a tariff different from the national tariff	✔
Publicly funded mechanisms exist to secure viability gap funding	✔
Duty exemptions and/or subsidies for mini-grids exist	✔
Technical standards exist detailing requirements for mini-grids to connect to the grid	✔
Environmental regulation on the disposal of solar devices exists	✘

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

The Tanzanian government considers rural electrification a key component of poverty reduction. Aside from grid extension, the Rural Energy Master Plan focuses particularly on mini-grids and stand-alone systems for rural electrification [1]. 100,000 households are expected to benefit from a performance based grant of the Rural Energy Agency to support mini-grids and other off-grid solutions [1]. Tanzania has one of the most extensive regulatory frameworks for mini-grids in Sub-Saharan Africa which includes provisions on licensing, tariff regulation and technical standards as well as more flexible guidelines for smaller projects [2]. It is estimated that at the beginning of 2016, mainland Tanzania already had at least 109 mini-grids installed serving approx. 184,000 customers [3].

ICT adoption & digital development

Digital technologies play an important role in the government's long-term strategy to transform Tanzania into a knowledge-based, semi-industrialised middle-income economy by 2025 [4]. The country has made substantial efforts to create an enabling environment through the provision of adequate regulation, competitive markets and infrastructural development [5]. In addition, Tanzania has one of the most advanced mobile money markets in Sub-Saharan Africa [4] and is an early adopter with regard to digital technologies, for instance in the e-health sector.

16 % of individuals use the internet (2017)[a)]

23.7 Mio. unique mobile subscriptions (2017)[b)]

37.8 % of rural population with mobile money account (2017)[c)]

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

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[1] Ministry of Energy and Mineral. 2015. Tanzania's SE4ALL Action Agenda. https://www.seforall.org/sites/default/files/TANZANIA_AA-Final.pdf (Accessed 04 July 2019).

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UGANDA

Uganda is a landlocked country with significant natural resources and an abundance of arable land. The economy has shown good growth rates over the past decade, but is vulnerable to adverse climate conditions, unrest in neighbouring countries and poor management of public investments. Uganda has one of the highest population growth rates in the world with the majority of its population living in rural areas. Despite significant progress, poverty remains an important challenge.

42.7 Mio. people (2018) a)

76 % live in rural areas (2018) a)

18.6 % of rural population with access to electricity (2016) b)

Source:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Programs to support the development of mini-grids exist	✔
Regulation clarifies what will occur when main grid reaches the mini-grid	✘
Mini-grids can be owned and operated by private operators	✔
Operators are allowed to charge a tariff different from the national tariff	✔
Publicly funded mechanisms exist to secure viability gap funding	✔
Duty exemptions and/or subsidies for mini-grids exist	✔
Technical standards exist detailing requirements for mini-grids to connect to the grid	✘
Environmental regulation on the disposal of solar devices exists	✘

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

The government of Uganda aims to achieve a rural electrification access rate of 26 percent by 2022 and achieve 100% by 2040 [1]. Electrification is to be reached mainly through grid extension. However, 140,000 additional installations of solar photovoltaic systems and mini-grid connections are envisaged [1]. Mini-grids are particularly suitable to electrify concentrated settlements in remote locations, such as the islands in Lake Victoria [2]. Several pilot projects have been launched in recent years, for example a project financed by the European Union and the German Federal Ministry for Economic Cooperation and Development which aims to promote mini-grids in up to 40 villages in Southern and Northern Uganda [3].

ICT adoption & digital development

Uganda has established a comprehensive and progressive framework to support the uptake of modern information and communication technologies (ICTs) and to spur Uganda's development towards a knowledge economy [4]. However, a low internet penetration rate and a large digital divide between rural and urban areas constrain the implementation of the Digital Uganda Vision [5]. Besides, digital skills and competencies need to be enhanced in order to leverage the potential of ICTs for productive uses [5].

23.7 % of individuals use the internet (2017) a)

17 Mio. unique mobile subscriptions (2017) b)

50.1 % of rural population with mobile money account (2017) c)

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:

[1] Rural Electrification Agency; Ministry of Energy and Mineral Development. 2013. Rural Electrification Strategy and Plan 2013 – 2022. http://www.rea.or.ug/resources/strategy%20and%20plan%202013-2022.pdf (Accessed 04 July 2019).

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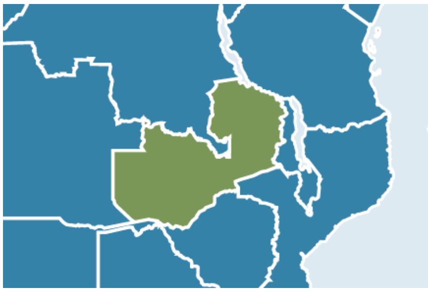
ZAMBIA

Zambia is a land-locked country in the centre of Southern Africa with abundant natural resources and one of Africa's largest copper producers. It is considered politically stable and has shown high economic growth over the past years. However, the economic performance of the country has particularly benefited urban populations and has not translated into equally significant gains in rural areas where poverty remains a major challenge.



17.4 Mio. people (2018)[a]

56 % live in rural areas (2018)[a]

6.5 % of rural population with access to electricity (2016)[b]

Source:
a) World Bank, World Development Indicators.
b) International Energy Agency. Energy Access Outlook 2017.

Mini-grid regulation – selected indicators

Indicator	
Programs to support the development of mini-grids exist	✔
Regulation clarifies what will occur when main grid reaches the mini-grid	✘
Mini-grids can be owned and operated by private operators	✔
Operators are allowed to charge a tariff different from the national tariff	✔
Publicly funded mechanisms exist to secure viability gap funding	✘
Duty exemptions and/or subsidies for mini-grids exist	✔
Technical standards exist detailing requirements for mini-grids to connect to the grid	✘
Environmental regulation on the disposal of solar devices exists	✔

Sources: World Bank, Regulatory Indicators for Sustainable Energy (RISE), http://rise.worldbank.org/.

Rural electrification & mini-grids

Zambia aims to achieve 51 percent rural electrification by the year 2030 [1]. Aside from standalone solar home systems, it is assumed that mini-grids will play an important role in supplying electricity to rural communities. Mini hydro power is perceived as having a particularly high potential [2]. After a successful first pilot of a solar mini-grid in 2009, further solar mini-grids are being developed with a combined capacity of at least 500 kWp to directly benefit public institutions, businesses and private households [3]. A regulatory framework for mini-grids has been approved by the Energy Regulation Board of Zambia in October 2018 and is currently in a testing phase [4].

ICT adoption & digital development

The development of information and communication technologies (ICTs) has been a priority for Zambia for already over a decade and spurred strong growth rates in the sector. In recent years, the framework conditions for the uptake of ICTs for socio-economic development have further evolved. These include for instance high-level government initiatives such as SMART Zambia launched in 2015 as well as the improvement of internet infrastructures such as cross-border fibre-optic connections [5]. Still, internet access, ICT affordability and ICT skills remain challenges to be tackled in particular in rural areas.

27.9 % of individuals use the internet (2017)[a]

9 Mio. unique mobile subscriptions (2017)[b]

25.5 % of rural population with mobile money account (2017)[c]

Sources:
a) ITU, World Telecommunication/ICT Development Report and database.
b) GSMA 2017: The Mobile Economy. Sub-Saharan Africa 2017.
c) World Bank, World Development Indicators.

Sources:

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Annex II: List of interviews

#	Date	Interviewee*
1	22 March 2019	Sustainable energy expert, GIZ, Kenya
2	29 March 2019	Project manager and renewable energy expert, UNIDO, Austria
3	8 April 2019	Representative of consulting and engineering firm for rural electrification, Germany
4	10 April 2019	Off-grid energy expert, GIZ, Kenya
5	12 April 2019	CEO of company providing solutions for rural development, India
6	16 April 2019	Representative of technology company providing centralised monitoring and control solution, Germany
7	17 April 2019	Renewable energy expert, GIZ, Germany
8	24 April 2019	Renewable energy expert, UNIDO, South Africa
9	25 April 2019	Representative of solar agro-tech start-up, Kenya
10	26 April 2019	Mini-grid expert, GIZ, Germany
11	30 April 2019	Renewable energy and energy efficiency expert, UNIDO, Austria
12	10 May 2019	Senior energy and innovation advisor, DFID, UK
13	16 May 2019	Off-grid energy expert, GIZ, Mozambique
14	20 May 2019	Rural electrification expert, GIZ, Senegal

* Names and company of interview partners have been anonymised.

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Funded by the ministries of research of the Federal Republic of Germany and the State of Brandenburg, the Institute for Advanced Sustainability Studies (IASS) aims to identify and promote development pathways for a global transformation towards a sustainable society. The IASS employs a transdisciplinary approach that encourages dialogue to understand sustainability issues and generate potential solutions in cooperation with partners from academia, civil society, policymaking, and the business sector. A strong network of national and international partners supports the work of the institute. Its central research topics include the energy transition, emerging technologies, climate change, air quality, systemic risks, governance and participation, and cultures of transformation.

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