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LEAP-RE
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Accurate map of digital technologies components and systems for mini grids at technical system and operational levels dedicated to African needs

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Summary

Map of Digital Technologies for Minigrids

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Accurate map of digital technologies components and systems for mini grids at technical and operational levels dedicated to African needs

SETADiSMA

Deliverable D13.4

This deliverable will report the results of the assessment and analysis of digital technologies for mini-grids at technical and operational system levels. This will be the incipit report of Task 13.2

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Acronyms

ANFIS	Adaptive neural fuzzy inference system
ANN	Artificial neural networks
AR	Autoregression
ARMA	Autoregression moving average
ARIMA	Autoregression integrated moving average
BES	Battery energy storages
CAPEX	Capital expenditures
COVID-19	Corona virus
DFI	Development financing institution
DG	Distributed generation
DSO	Distribution system operators
ECOWAS	Economic Community of West African States
EPC	Embedded PCs
GA	Genetic algorithm
GOOSE	Generic Object- Oriented Substation Event
ICT	Information and communication technologies
IEA	International Energy Agency
IED	intelligent electronic devices
IoT	Internet of things
IRENA	International renewable energy agency
LAN	Land Area Network
MA	Moving average
MAC	Media Access Control Layer
MMS	Manufacturing Message Specification

NWP	Numerical weather prediction
NZE	Net Zero Emission
OGS	Off-grid solar
OSGP	Open Smart Grid Protocol
OSI	open system interconnection
P2P	peer-to-peer
PAYGO	Pay As You Go
PV	Photovoltaic
RE	Renewable energies
SV	Sampled Values
SCADA	Supervisory Control And Data Acquisition
SDG	Sustainable Development Goals
SG	Smart grids
Se4All	Sustainable Energy for All
STEPS	Stated Policies Scenarios
SVR	Support vector regression
TSO	Transmission system operators
WAN	Wireless Area Network
WHO	World Health Organization
WT	Wavelet transform

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1. Introduction

In 2017, approximately 600 million people in Africa lacked access to electricity. Access to clean, reliable and affordable energy is one of the main challenges for next years for many countries in Africa continent. This is particularly the case in rural and more remote areas which are often not connected to the national electrification. The unavailability of modern energy affects African income generation ability, decelerates attempts to eliminate poverty, deteriorates their health conditions and contributes to global deforestation and consequently to climate change. In addition, with the rising electricity needs of industrial clients and urban households, the feasibility of centralizing the national grid will shrink at an alarming rate. For these areas, decentralized energy technologies can provide viable solutions for energy access. Mini-grids are expected to gain an increasing role in this regard since they can both to provide electricity demand of small households and to assure enough energy for productive uses. Small-scale renewable energy supply can offer rural communities modern energy services. Considering technical, economic, social and environmental aspects, the development models for the continent driven towards the application of renewable energy (RE) smart grids for the development of rural Africa regions with poor, or even no, electrification.

Over the past decades, the digitalization trend has entered the mini-grid sector leading to the development of innovative approaches and technologies to improve mini-grids and related services. In this context, ICT and Internet of Things (IoT) approach play essential role in smart grids, which are the enabler of the autonomous local and remote monitoring and control of the power systems. Moreover, smart grid applications such as load control and demand response, and energy trading are dependent on the ICT system. The importance of ICT & IoT are even highlighted in rural environments and surroundings, as the operation and maintenance off grid smart grids and standalone systems is one of the weakest links, from this system sustainability perspective. Besides IoT between end devices in smart grids, ICT system provide also access to digital world, global markets, and information for the end-users of the power grids. In fact, approximately 3.5 billion people do not have access to internet. This can be considered as limiting factor when considering the quality of life, as for instance access to information is crucial in education. Again, education and training are essential when the livelihood of the remote rural under-served communities is to be increased. In this regard, particular emphasis will be given to the promotion of productive uses of electricity and in this context, the report also aims to provide a comprehensive overview of the interconnections between digital technologies and mini-grids.

Thus, not just energy revolution via electricity access for rural Africa is important, but also digital revolution is to be consider with connectivity solution, for example based on lightweight private 4G LTE technology; micro base stations, and mobile networks , for the end users of the rural communities. Digitalization commonly refers to improving, enabling or transforming business models thanks to digital technologies and digital data, generating new types of value.

The “mobile revolution” is often considered as an example of technological progress in Africa: the success of the mobile phones and connectivity has been so fast that it has effectively overcome the population needs and habits. One of its consequences was the creation of “mobile money services” as a bottom-up remedy to the widespread lacking access to banking and financial services.

With available of connectivity, for instance micro-entrepreneurs in rural communities, via access to local and global markets and value chains can start and generate new business, which again servers the whole community and increases its livelihood. Moreover, supportive actors and stakeholders e.g., development banks and local private investors are needed to fund and support the initializing and implementation of these new-built smart grids, as well as for introducing and generating new business for the entrepreneurs. This is part of the analysis of viable business models in these surroundings; the smart grid concepts need to be affordable and sustainable for the community.

The present report is organized as follows:

- following the introduction, Section 2 provides basic background information on status and deployment of mini-grids in Sub-Saharan Africa;
- Section 3 describes the architecture of a mini grids, its main components, protocols for communication, and management, storage and backup of the data.
- Section 4 and 5 provide information on the development of digital technologies and applications of ICTs in the context of mini-grids in Africa;

• Section 6 draws conclusions and reflects on how digital technologies could contribute to meeting the aforementioned requirements for the design of sustainable and affordable smart grids.

2. African Electricity Access and mini-grid landscape

2.1. African electricity access

In Africa, the number of people each year gaining access to electricity almost tripled from 8 million between 2000 and 2013 to 24 million people between 2014 and 2019, outpacing population growth. As a result, the number of people without electricity, which peaked at 613 million in 2013, declined progressively to around 572 million in 2019", says the International Energy Agency (IEA) in its 2022 SDG7: Data and Projections Report. Much of this dynamism comes from a small handful of nations, most notably Kenya, Senegal, Rwanda, Ghana, and Ethiopia, whereas more than 40% of Sub-Saharan African countries still lack official electricity access targets. Electricity access substantially limits modern economic activities, public service delivery, and quality of life. Furthermore, it severely limits the use of growing technology in sectors such as banking, education, agriculture, and finance, which could otherwise help to alleviate some of Africa's most pressing problems, such as poor productive employment possibilities and limited healthcare.

A joint report released in 2021 by the International Renewable Energy Agency (IRENA), the (IEA), the United Nations Statistics Division (UNSD), the World Bank, and the World Health Organization (WHO), who are the custodian agencies of Sustainable Development Goal (SDG) 7, [1]"Tracking SDG 7: The Energy Progress Report", which examines the progress made toward the achievement of SDG 7, "ensure access to affordable, reliable, sustainable and modern energy for all" by 2030, "While progress has been made toward increasing electricity access globally—441 million more people have electricity in 2019 compared to 2010—the report highlights how the trajectory has been further diverted due to the COVID-19 pandemic that

[1] Tracking SDG 7: The Energy Progress Report 2021 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/SDG7_Tracking_Progress_2021.pdf

places additional burden on supply chains and consumer's income, and is set to increase the deficit of electricity access in 2020.

In a 2Forbes article in 2021, "Africa Needs Electricity Now More Than Ever, Especially to Keep COVID-19 Vaccines Cold" emphasis was placed on the insufficient access to energy, the author wrote:" Electricity is the lifeblood of any economy". Gross Domestic Product per capita is generally three to five times greater in North Africa where less than 2% of the population is without reliable power, IRENA says. In sub-Saharan Africa, the problem is far more acute and will require billions in new investment".

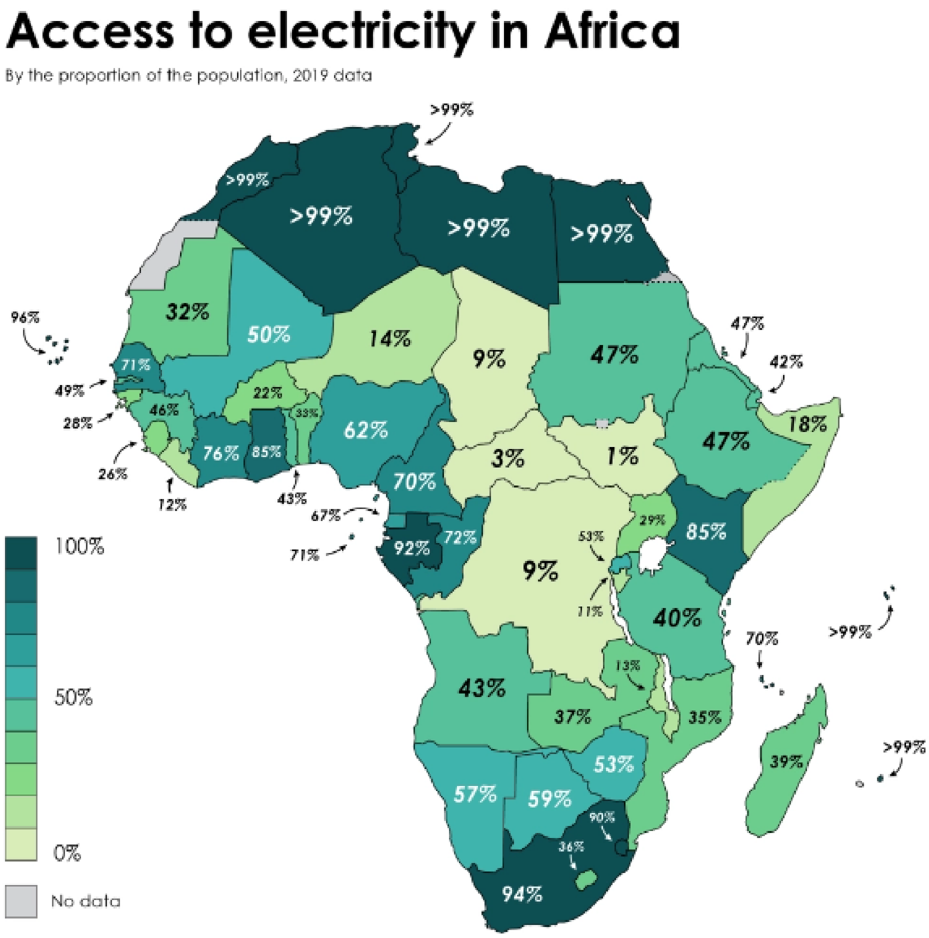

Figure 1: Map of the access to electricity in sub-Saharan Africa. Source: IEA (2022b)

[2] Africa Needs Electricity Now More Than Ever, Especially To Keep COVID-19 Vaccines Cold https://www.forbes.com/sites/kensilverstein/2021/05/02/africa-needs-electricity-now-more-than-ever-especially-to-keep-covid-vaccines-cold/?sh=5642fecb5806

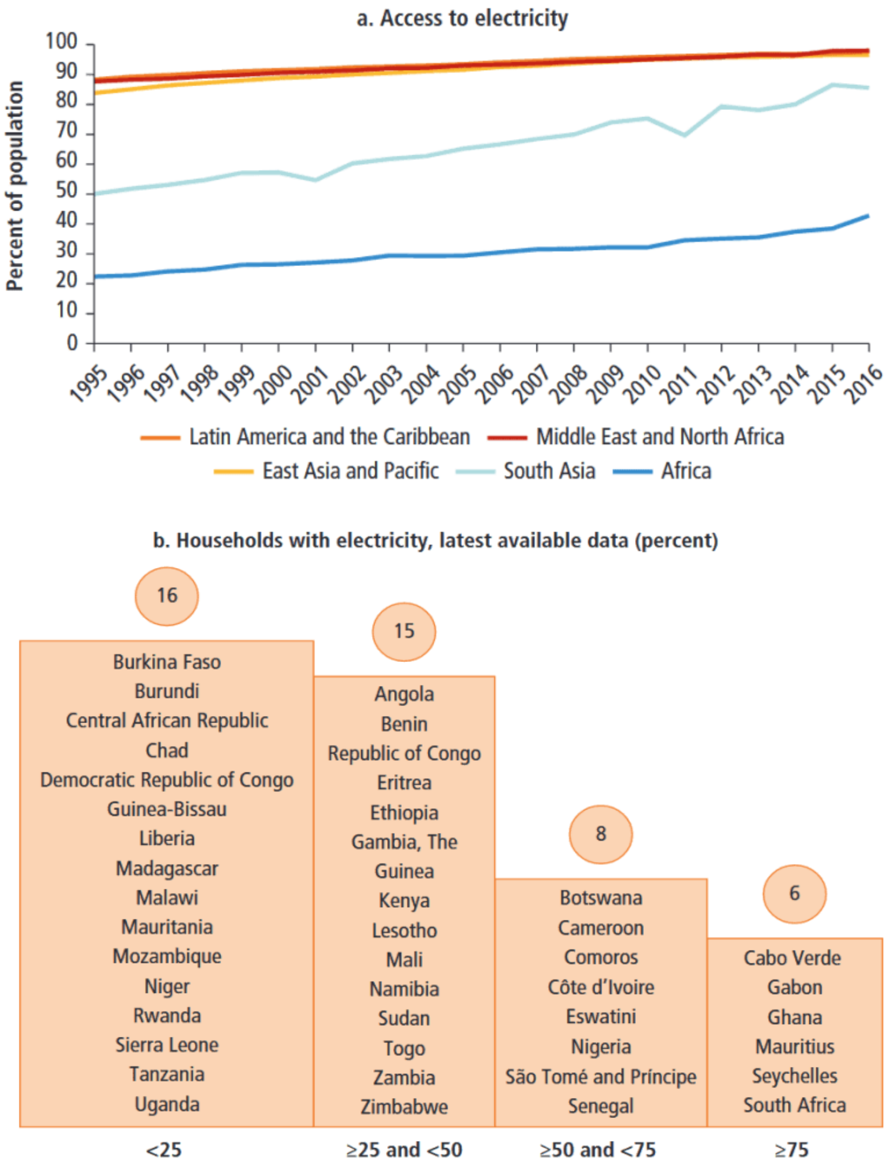

Figure 2: Access to electricity in Africa based on percentages of total population and households. Source: World Bank (2019)

Shortages of electricity not only affect economic productivity; it also manifests itself in hundreds of thousands of deaths annually and reduction of people's quality of life due to the use of wood-burning stoves for cooking; handicaps the operations of hospitals and emergency services; compromises educational attainment; and drives up the cost of doing business. As without power, "clinics cannot deliver babies safely at night, children cannot study longer, businesses close at sunset and vaccines cannot be reliably refrigerated," observes Vijay Modi,

a researcher on alternative fuels for Africa at Columbia University in New York. Hence the affirmation that energy access for all is therefore one of the key drivers of inclusive growth.
Despite decades in which African governments heavily subsidized power rates and promoted rural electrification campaigns, some 550 million people, or almost 75 percent of the population of sub-Saharan Africa, still do not have access to electricity. In 2004 in East Africa, less than 3 percent of rural people and 32 percent of urban residents were connected to their national grids. According to the World Bank, only Côte d'Ivoire and Zimbabwe exceed 70 per cent coverage.
The problem of energy access in Sub-Saharan Africa has multiple dimensions, with large parts of the population lacking a reliable supply of electricity and affordable modern cooking fuels: from insufficient power generation capacity to difficulties in managing energy infrastructure and attracting investments in the sector, to challenges in serving low-income users. Africa's energy potential, especially renewable energy, is enormous, yet only a fraction of it is being currently employed. Lack of access to electricity is endemic in Africa regardless of income.

The International Energy Agency (IEA), in its 32022 SDG7: Data and Projections Report, estimates the number of people without electricity access rose slightly to about 770 million in 2021, breaking the downward trend in the years prior to the Covid-19 pandemic. Most of the increase was in sub-Saharan Africa, which was already home to 74% of the global population without access prior to the pandemic - four in five people without access now live in sub-Saharan Africa. To achieve full access by 2030, 100 million people must be connected each year.

However, the world is not currently on track to reach this goal. In the 4IEA Stated Policies Scenario (STEPS) – a more conservative benchmark that looks at existing or announced policies – some 672 million are projected to remain without access in 2030, 85% of whom will be in Africa. On the other hand, many developing countries in Asia are well on track to achieve

[3] IEA (2022), SDG7: Data and Projections, IEA, Paris https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity
[4] IEA Stated Policies Scenario (STEPS) https://www.iea.org/reports/world-energy-model/stated-policies-scenario-steps#abstract

near universal access by 2030. This means the access rate will have to more than triple between now and 2030. In Sub-Saharan Africa alone, this would mean connecting around 85 million people each year through 2030.

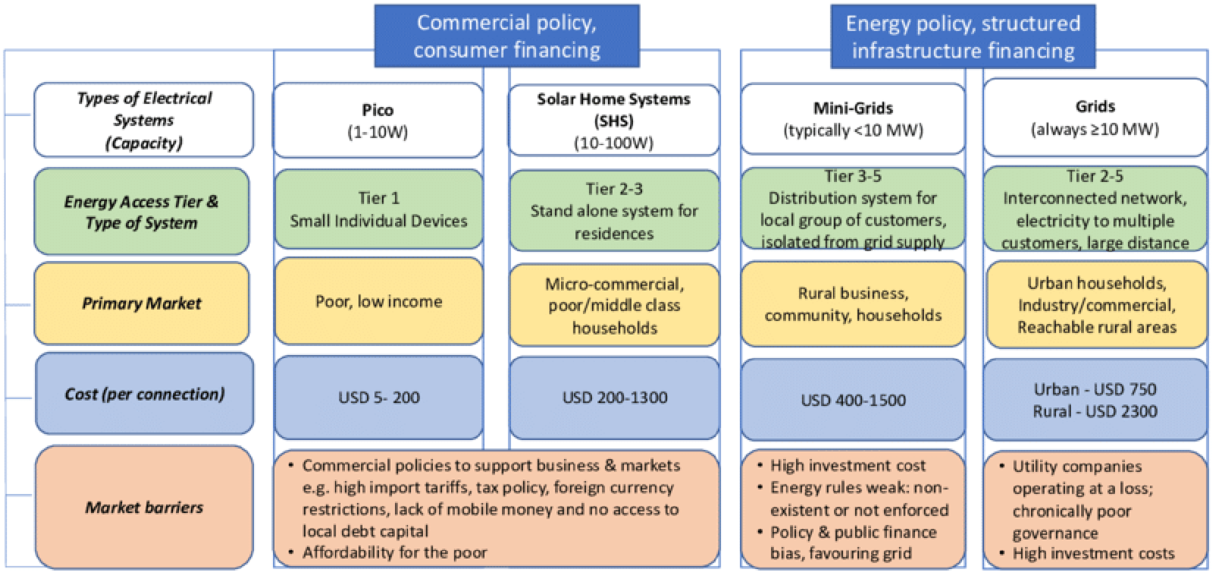

Figure 3: Types and Characteristics of Electricity Access Options in Sub-Saharan Africa. Source: Corfee-Morlot, et *al*. (2019)

Achieving full electricity access by 2030 requires annual investment of just over USD 35 billion, or only 2% of current global energy investment. However, current investments in power access are well below this. Financing represents one of the major barriers to achieve global access since many of the projects require public support via concessional and blended finance structures, while low demand potential in some remote areas can deter private capital.

Africa's increase in the number of people without access contrasts with Asia, where the rollout of grid connections and distributed electricity access solutions was supported by more concerted policies and easier access to financing. While the gains in Asia slowed down during the pandemic, they still proved more resilient than in Africa, which could serve as a good case study for Africa to follow in order to meet our energy access targets.

The IEA [5]Net Zero Emissions by 2050 scenario (NZE) illustrates a trajectory to achieve full access to electricity by 2030. Slightly more than half of the people gaining access in the NZE by 2030 do so through decentralised solutions, including mini-grid and stand-alone systems, which are 90% based on renewable solutions.

After 2030, grids will reach most of the population that initially gained access through off-grid solutions, emphasising the importance of grid-compatibility for the off-grid systems being built today. Under this scenario, only the most remote users will not have a grid connection by 2050.

2.2. Mini-grid development on the continent

2.2.1. Current development

African policies have emphasized the expansion of grids in rural, peri-urban, and metropolitan areas, with a focus on boosting national grid coverage. Mini-grids are a feasible alternative to grid expansion as renewable energy generation technologies become more economical and efficient. They can provide electricity to millions of people living in rural and isolated communities with dense populations, while standalone solar home systems can serve areas with dispersed populations.

[6]Energy developers have believed that mini-grids offer a cost-effective solution for providing communities and businesses in sub-Saharan Africa with low-cost, reliable, and clean power—particularly in places out of reach of existing power grids. Most modern mini-grids are powered by an energy source—usually solar panels—combined with battery storage and a local distribution system. They supply power to homes, small businesses, and industry—particularly in areas beyond the reach of the main grids. As the costs of mini-grid components such as solar and battery energy storage technologies decrease, solar mini-grid solutions are becoming more economically viable.

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[5] Net Zero Emissions by 2050 scenario (NZE) - https://www.iea.org/reports/world-energy-model/net-zero-emissions-by-2050-scenario-nze

[6] International Finance Corporation: https://www.ifc.org/wps/wcm/connect/news_ext_content/ifc_external_corporate_site/news+and+events/news/insights/africa-mini-grids

[7]When African governments started building mini-grids in the 1960s, diesel generators were the most popular energy source – they were relatively straightforward to run and solar technology was still in its infancy. Governments had the existing diesel infrastructure knowledge and mini-grid developers had enough experience to scale mini-grids quickly and effectively.

Since then, solar panels in Africa have gone through something of a revolution and between 2009 and 2015, solar PV module prices fell by 80%. Solar-powered mini-grids are now often cost-competitive with diesel-powered grids, offering governments an opportunity to drastically reduce carbon emissions, and households the prospect of cleaner air.

When combined with efficient and environmentally sustainable battery storage, solar mini-grids present a compelling economic case for rural communities in Africa. According to the IEA, they are essential to future rural electrification in Africa. Consequently, many African governments, including Ethiopia, Kenya, and Nigeria, are making mini-grids a pillar of their national electrification plans, complementing grid extensions and solar home systems.

Reaching the remaining unserved population, which includes those connected to frail and overburdened urban grids, as well as those living in remote areas, fragile and conflict environments, will necessitate strong policies, increased private financing, and comprehensive approaches to national electrification planning, which includes main grid extensions, mini-grids, and off-grid solar systems. [8]According to estimates, small grids will need to account for 40% of all installed capacity in order to ensure universal access to energy by 2030. At the moment, total small grid investment in Africa and Asia in countries with low levels of power access totals $5 billion.

[7] ODI : https://odi.org/en/insights/how-solar-mini-grids-can-bring-cheap-green-electricity-to-rural-africa/

[8] Mini-grids for Half a Billion People: Market Outlook and Handbook for Decision Makers: https://openknowledge.worldbank.org/handle/10986/31926

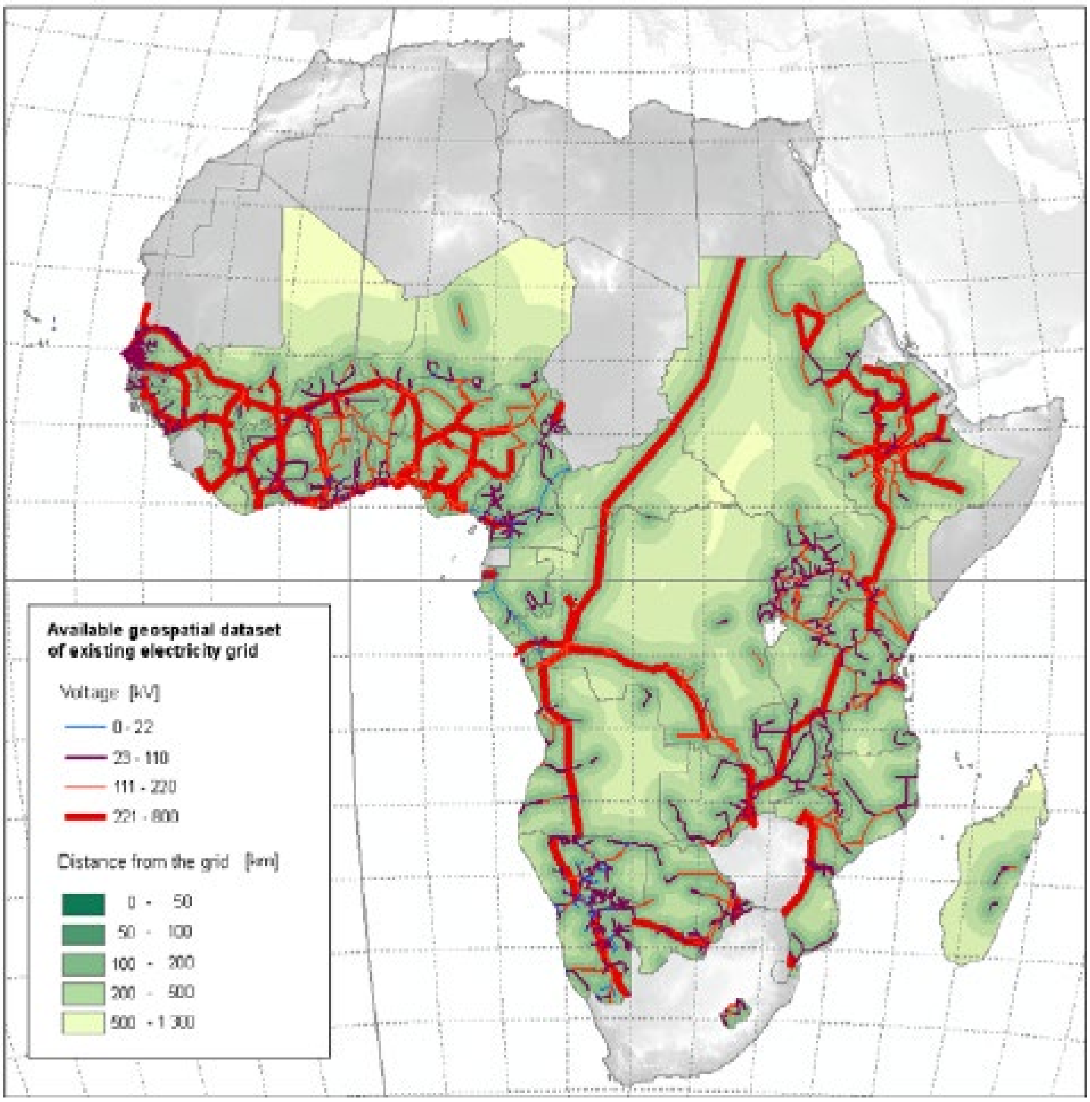

Figure 4: Map of the geospatial dataset of existing electricity grid in sub-Saharan Africa and distance from the grid. Source: Szabó et al. (2011)

[9]The available geographically explicit information on the existing electrical transmission and distribution lines in Sub-Saharan Africa was acquired through a comprehensive data mining activity (map). The data was acquired from publicly available [10]web sources, regional institute databases, and [11]individual specialists. However, the digital dataset of the power grid is still

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[9] Energy solutions in rural Africa: Mapping electrification costs of distributed solar and diesel generation versus grid extension:https://www.researchgate.net/figure/Available-geospatial-dataset-of-existing-electricity-grid-in-Sub-Saharan-Africa-and_fig3_252684941.

[10] AICD 2009 Africa Infrastructure Country Diagnostic (AICD)

[11] Kaijuka E 2007 GIS and rural electricity planning in Uganda J. Clean. Prod.
Szab´oS,B´odis K, Girbau-Garc´ıa Z, Huld T,Moner-Girona M and Pinedo Pascua I 2010 Building the African renewable energy platform integrating support tools for a sustainable energy development in Africa *Proc. 25thEuropean Photovoltaic Solar Energy Conf. and Exhibition*.

incomplete after data integration, covering 33 of the 48 countries unevenly. When contemplating grid extension, the load density (measured in households km2), the number of houses connected, and line length, among other factors, impact the cost of energy. This information is still inaccessible in most rural parts of Sub-Saharan Africa.

As part of the [12]State of the Global Mini-grids Market Report 2020, a Mini-Grids Partnership report published by BloombergNEF and Sustainable Energy for All (SEforALL), a benchmark to measure progress in the mini-grid sector for decision-makers, latest updates on the global mini-grids market, key trends in the industry, as well as research across various cross-institutional stakeholders is provided, detailing the current state of the mini-grid sector.

The authors of the report identified 7,181 mini grid projects in Sub-Saharan Africa, Asia and small island nations with some in Latin America, as of March 2020. As many as 5,544 mini-grids were operational, of which 63 percent were solar or solar hybrid systems, 21 percent hydro, and 11 percent diesel/heavy fuel oil. The mini-grids already installed today represent only a small fraction of the total needed for full rural electrification.

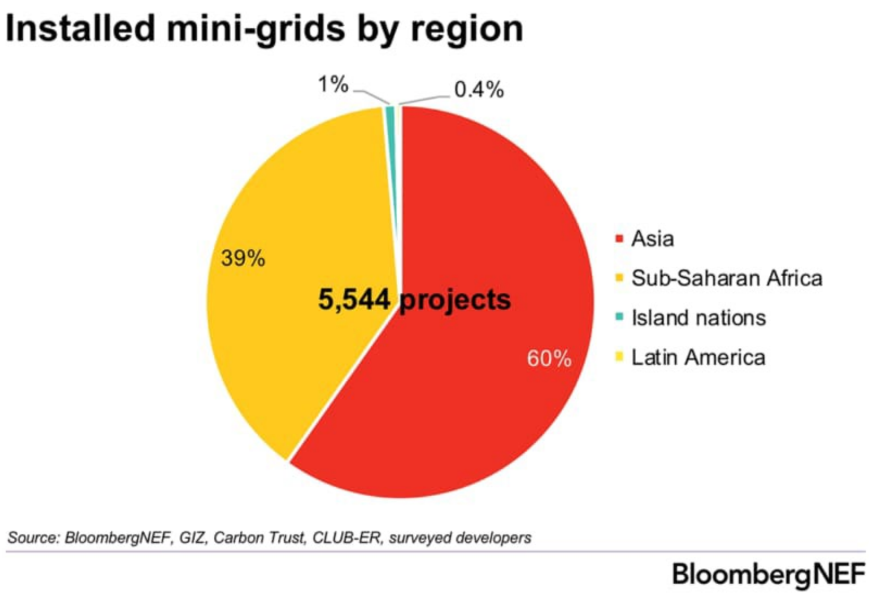


Figure 5: Installed mini-grids by region. Source: BloombergNEF & SE4All (2020)

[12] State of the Global Mini-grids Market Report 2020: https://minigrids.org/wp-content/uploads/2020/06/Mini-grids_Market_Report-20.pdf

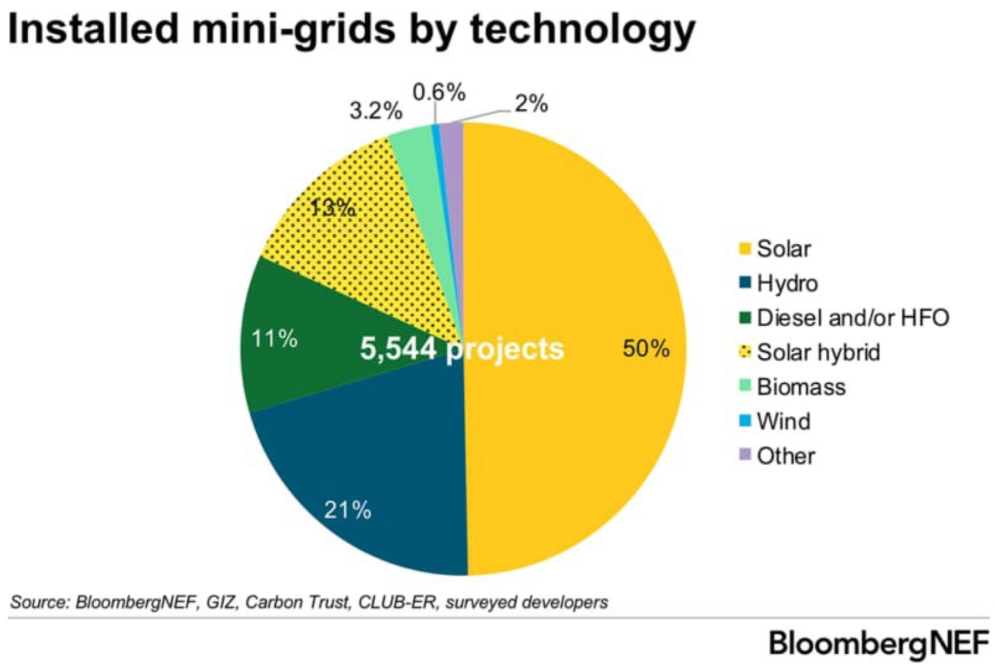


Figure 6: Installed mini-grids by technology. Source: BloombergNEF & SE4All (2020)

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 [13]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.

Whilst these numbers are dynamic and constantly changing, they also highlight how differences in demand, infrastructure and regulatory frameworks influence the diffusion and penetration of mini-grids. Mini-grid approaches provide a variety of new prospects for rural electrification in Africa, but experience shows that in many contexts, significant hurdles remain to be solved before they can be scaled up.

[13] State-of-the-Art of Mini-grids for Rural Electrification in West Africa: https://www.mdpi.com/1996-1073/14/4/990/pdf

2.2.2. **Sustainability** challenges

Despite improving conditions for mini-grids, a lot of challenges remain, particularly in terms of sustainability. To begin with, mini-grid implementation is still heavily influenced by donors or subsidies. It also depends heavily on the regulatory settings of individual countries, and the lack of a clear policy environment has increased uncertainty and deterred private investment. Another important consideration for a mini-long-term grid's viability is whether and when the national grid will reach a given area. Furthermore, there are technological challenges associated with establishing and sustaining mini-grids in rural locations over time, particularly in terms of consumer safety. In this report, we highlight some of the most pressing sustainability issues in the context of mini-grids.

A. No policy or regulations to protect mini-grid asset cash flows

Mini-grid projects are hampered by ambiguous rural electrification policies, a lack of flexibility in determining mini-grid pricing, and complex and lengthy licensing processes. Electricity tariffs are also becoming more politically and publicly sensitive, making flexible pricing setting difficult (e.g., in Tanzania). In order to sustain and scale mini-grids and encourage private investment in the sector, there is great need for a clear policy and regulatory model to be adopted by African governments. Some governments, such as that of Nigeria, have set regulations to reduce the risks to a mini-grid if the main grid arrives later at the same location, however a larger number of governments lack regulations that protect isolated mini-grids if the main grid arrives. Without such regulations, the state may expropriate mini-grid assets with minimal compensation, or in the worst case, they can be stranded. Even when there are regulations in place, governments and state-owned utilities do not always enforce them

In an ideal policy and regulatory scenario:

- there are clear goals for electricity access by technology with strong political initiatives set by governments;
- single points of authority with powers to streamline the licensing process, relax size thresholds for required licensing, deregulate tariffs, and build a robust set of rules around grid arrival to protect isolated mini-grid assets are established; and

- mini-grid owners have reassurances that, should grid arrival occur, a range of options would be available to them, such as receiving compensation and operating alongside the main grid (e.g., Nigeria).

B. No financing of the mini-grid sector

Most mini-grid developers have relied on public funding such as grants from governments, development finance institutions (DFIs), donor agencies and foundations. At the moment, there exists a lack of pure commercial financing as the mini-grid market lacks scale, developers' project track records are limited and residential consumers have limited power demand as well as limited ability to pay.

According to the Mini-grids Funders Group, 14 funders had approved a total of USD 2.07 billion by March 2020, of which only 13 percent had been disbursed. While the situation on the ground is likely to be better than the data suggests, it is evident that acquiring finance, and hence pushing projects forward in the context of mini-grids, can take time. Governments must take bold steps and create strong regulatory frameworks to encourage the development of mini-grids, which can in turn attract more commercial financing.

C. Limited ability and willingness of local consumers to pay

Mini-grid developers are increasingly looking for sites with productive-use customers (i.e., commercial and industrial), and innovating new financial models to encourage these customers to use more electricity. The electricity from solar hybrid mini-grids however, is still expensive for many rural customers who have limited ability and willingness to pay. While rural communities do have productive-use customers (e.g., those using agricultural equipment), who can help boost revenues for the mini-grid, in practice, they do not always use electricity during the day when the photovoltaic (PV) system generates electricity. Public funding continues to be critical to the economic viability of rural mini-grids. Developers can also improve revenues through business models or initiatives that prompt customers to use more electricity in the day. African governments can contribute in providing leeway to developers to set their tariffs flexibly, especially for small-scale projects or by subsidizing tariffs to overcome the barrier of high electricity costs to consumers.

D. No impact assessment and reporting for the mini-grid sector

There is no widely agreed method for collecting and reporting impact data for energy access projects. Calculating the number of persons who have access to power is simple, but it does not account for how energy access programs have benefited rural areas. Collecting data, measuring, and reporting the sector's impact is essential for attracting investors interested in and willing to participate in projects that have positive environmental and social benefits. Some organizations have developed innovative impact assessment metrics for off-grid projects and collected impact data. The mini-grid sector needs to assemble impact data for mini-grid projects using some of the established metrics, to measure current performance of the sector and inform on development areas.

For mini-grids to be economically and financially sustainable, African governments should integrate them into national electrification plans, policy and tariff frameworks, encourage commercial financing, and promote impact assessment and reporting of data in the mini-grid sector. With less infrastructure in rural regions than any other region, African governments now have a unique chance to lead the way and demonstrate how mini-grids can supply rural energy that is cleaner, cheaper, and more inclusive.

2.2.3. Market needs

According to the State of the Global Mini-grids Market Report 2020, 238 million households will need to gain electricity access in Sub-Saharan Africa, Asia and island nations by 2030 to achieve universal electricity access. Mini-grids can serve almost half of this total – an estimated 111 million households. This will require capital investment of USD 128 billion, 78 percent higher than the estimated capital investment in a business-as-usual scenario.

Mini-grids technology is the most suitable option for many low- and medium-density areas and can address a larger number of low-income families more economically than the alternative options. The market for mini-grids remains nascent, and mini-grid projects often offer the least-cost option for delivering power to rural citizens who lack energy access. Despite this, there is still a lot of opportunity for improvement. Furthermore, while some mini-grids have been financed by commercial financiers and corporations to date, most projects still require some type of public backing or guarantee. Without subsidized support, the mini-grid sector has yet to reach a tipping point where it can expand exponentially.

Africa has one of the world's highest demands for mini-grids. In total, 47 million people are connected to 19,000 mini-grids around the world, with over 2,500 of them being operational clean-energy mini-grids. However, to provide energy to 440 million people, an additional 180,000 mini-grids would be required. According to the World Bank, Africa requires 140,000 of these, which would be a huge step toward achieving the 2030 target of universal energy access.

3. Overview of digital technology applications in the mini-grid sector

3.1. Digital technology applications in mini-grids

The literature analysis undertaken highlights the current status of research and applications of the digital technologies in the energy access sector resp. mini-grids in Africa, by identifying and examining the main research avenues in the field. The dataset for the analysis was gathered and compiled using online database: ScienceDirect, Google Scholar and the Association for Computing Machinery (ACM). The research was carried out with articles published or accepted for publication from the year 2000 to the year 2021, and featuring in journals of the academic areas related to the fields of energy, renewable energies, energy policy, energy economy, technology, engineering. The terms used for the research were: “Digitalisation” “energy”, “mini-grid”, and “Africa” in their titles, abstracts or keywords. The survey yielded after cleaning of duplicated articles, about 720 articles.

Through a co-occurrence analysis conducted with the software VOS viewer (Jan and Waltman 2021), a graphic visualisation of the different nodes of network of information was identified from the different articles (Donthu et al. 2020; Mas-Tur et al. 2021). The software facilitates the interpretation of bibliometrics maps, and identify thematic clustered in the dataset, highlighting therefore the correlation between different thematic/work conducted in the field. The analysis highlights different thematic clusters of the application of digital technologies in the energy sector as follow and highlighted in the following Figure 7 with specific colour codes. The thematic clusters are declined as follows based on the different elements they encompass: Electric and energy (heating) distribution networks (1) with focus on optimization of energy storage systems, automaton of processes and controls within energy systems; Electric power transmission network, digital twin (technologies) and asset management including power grids, electric utilities; Renewable energies and smart grids; Smart maintenance, innovation, circular economy and energy transition; Industry 4.0 and sustainability including in manufacturing and efficient resource and supply chains; Advanced analytics, machine learning and digital storage; Energy efficiency and energy management; Energy investments and policy; Automation and decision making; Power markets and climate change; Economic and social effects; Life cycle and architectural design; and proactive maintenance.

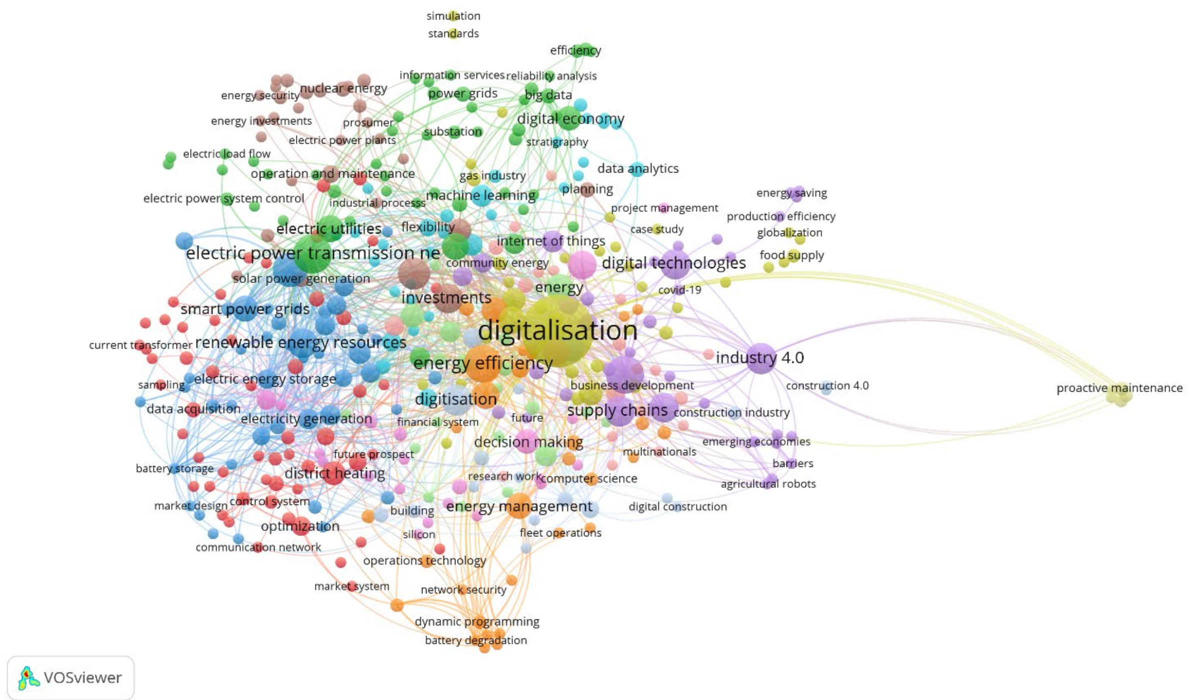


Figure 7: Co-occurrence map of the searched keywords.

While this figure represents a comprehensive cloud of networks o node within the wide energy sector, the specific sector of mini-grid also presents a wide range of application of digital technologies. Indeed, a recent study from the Institute for Advanced Sustainability

Studies (2019) further refines the scope of digital applications in the mini-grid sector. it also structures the different applications within a very well-defined frame based on the different functionalities of mini-grid systems as well as the associated value chain as highlighted on the Figure 8 below.

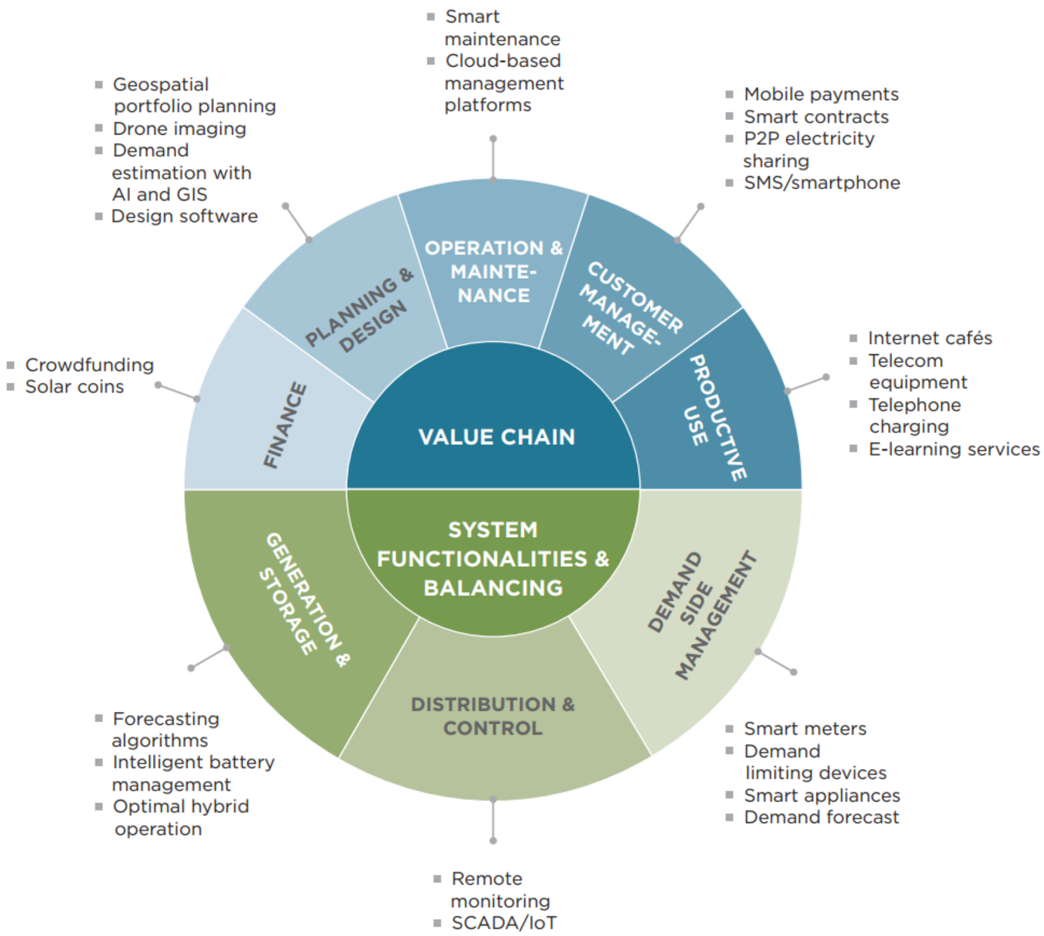


Figure 8: Digital technologies applications in mini-grid. Source: IASS (2019).

It shows the potential use cases and areas where digital advancements may improve mini-grid systems operation and performance while providing avenues for more sustainability. The figure highlights two degrees of application with underlying sub-categories as follows:

- System balancing and technical functions, involving generation and storage Control and distribution Management of demand; and

- Applications at the value chain level of the mini-grid, such as finance Design and planning.

3.1.1. System and technical functionalities

3.1.1.1. Forecasting algorithms

Forecasting algorithms play a critical role nowadays in the design of energy system and mini-grid in particular with the prediction of future electricity load and power generation. Indeed, it is critical to properly estimate the current and future demand in a community prior to designing the systems and ensuring an optimal an up-front investment cost. In this regard, and in the context where estimates have to be made regarding electricity demand in an isolated off-grid area, the deterministic approach is often used although it yields less accurate results but sufficient for investment sizing. this approach is further complemented with the stochastic methods, building on bottom-up approach and mathematical models allowing for more accurate results for the latter phase/stages of the design the mini-grid system (Herraiz-Cañete et al. 2022). The implementation of emerging technologies such as machine learning and artificial intelligence in forecasting further upgrade and provide greater accuracy to the prediction models. Indeed, Antwi & Al-Dherasi (2019) reported that Artificial intelligence-based forecasting algorithms yields much more accuracy in results compared to other forecasting methods. It builds on the constant need to improved existing processes in view of achieving optimal utilisation of the resources. However, due to the cost associated to this technology, its implementation can be limited for its appropriation to every sector (Antwi & Al-Dherasi 2019). In the energy and mini-grid sector specifically, AI can be used is several ways to optimise both for energy generation and consumption, contributing to providing mini-grid customers with renewable and affordable electricity from complex sources in a secure manner, while at the same time providing these customers with the opportunity to use their own energy more efficiently through its application in forecasting. One the one hand, it can be used to forecast the different environmental and weather parameters as well as power outputs from variable renewable energy sources such as solar panels and wind turbines.

Indeed, wind and solar energy are weather-dependent resources that vary from minute to minute, hour to hour, and year to year. Voltage fluctuations and intermittent power output are caused by the instabilities of renewable energy sources, making it difficult to sustain and plan power system operations. Similarly, throughout a calendar year, power usage displays seasonality. To solve the supply-demand mismatch problem, creating adequate forecasting technology to estimate power output and load demand is critical. Based on the energy management need, the forecasting time horizon is characterized as extremely short-term (from a second to half an hour), short-term (half an hour to 6 hours), medium-term (6 hours – 1 day), and long-term (1 day – 1 week). For example, extremely short-term forecasting tries to provide dynamic management and load monitoring for renewable power plants. Energy flow between power sources, loads, and storage devices is scheduled using short-term forecasting. Price settlement, load dispatch, and maintenance scheduling are all handled by medium- and long-term forecasting, respectively. To anticipate wind speed or/and wind power on various prediction scales, a variety of approaches have been developed and integrated. The extensively utilized forecasting tools created in the current case studies may be grouped into three approaches: physical model, statistical model, and computational intelligence model. The numerical weather prediction (NWP) model is the foundation of the physical method, in which atmospheric mesoscale models or global databases of meteorological datasets are used to represent the variability of meteorological processes.

The forecasting value has a linear association with historical data over a specific time period, according to statistical methodologies. Autoregression (AR), moving average (MA), autoregression moving average (ARMA), and autoregression integrated moving average (ARIMA) are some of the most often used statistical approaches (ARIMA). Meanwhile, the Box-Jenkins method is a useful tool for identifying time series components and parameters, while the Kalman filter technique, also known as a parametric model, is used with historical data. As a result, the artificial intelligence method ignores physical processes involving input variables and output performance in favour of a “black box” made up of a single model or a hybrid model. Fuzzy logic, artificial neural networks (ANN), support vector regression (SVR), wavelet transform (WT), genetic algorithm (GA), and expert systems are some of the most often utilized single models. To improve predicting accuracy, the hybrid system will combine one or more algorithms. The adaptive neural fuzzy inference system is the most frequently acknowledged hybrid model (ANFIS) (Xiandong and Ma 2018). Figure 9 below gives a quick overview of the different forecasting methods used in the sector.

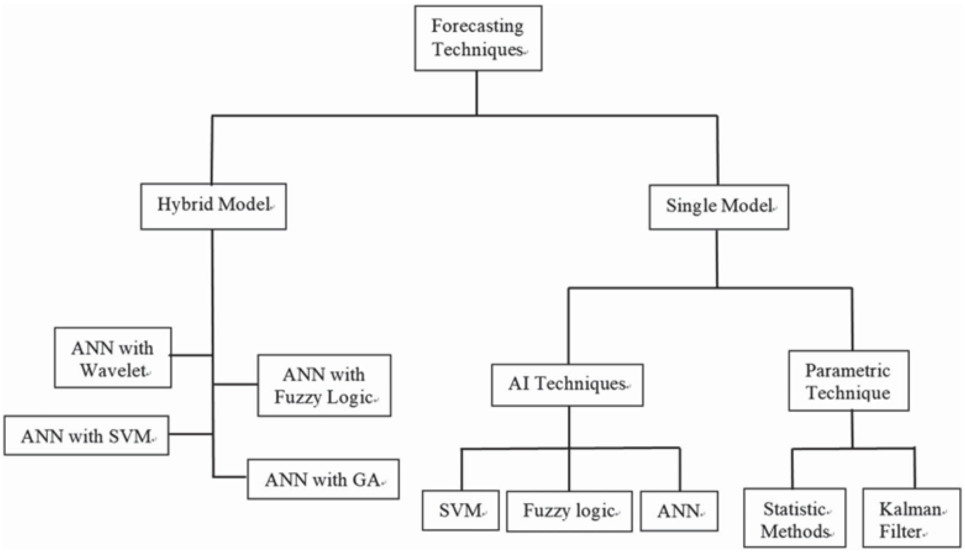


Figure 9: Forecasting techniques. Source: Xiandong and Ma (2018).

Although, evidence of research on the implementation of such algorithms in mini-grid on the continent is limited, several private sector actors such have been implementing the concepts to design modular, plug-and-play mini-grid system that can be scaled up or down adapting in real time to the generation requirements and constraints as well the demand constraints within the beneficiary community (Modularity grid 2022). Recent research tried to implemented AI genetic algorithm to implemented an efficient energy management at household level. It investigated the optimisation of energy consumption at household level in mini-grid in Africa (Abdulaziz 2020).

3.1.1.2. *Intelligent battery management*

Most of the mini-grid on the continent nowadays on the continent are hybrid trying to harness the full potential of available renewable energy resources. Given the nature of such resources to be mainly variable depending on weather parameters for wind and solar energies, very often the mini-grid designs allow for back-up systems such as diesel generator, or battery storage to cope with the limited production from the variable sources. However, ensuring the efficient management of the battery is something challenging. The use of digital technologies can allow the development of optimal energy management systems that can interact with the mini-grid controller to define with a level of accuracy when to use electricity from the battery in an efficient manner. In addition, using appropriate load and generation profile in renewable based-systems (e.g., solar PV), in combination with accurate weather forecast, more optimized battery management can be design shaving peak demand and reducing the daily energy cost via increased long life of the installed batteries (Spertino et al. 2019).

3.1.1.3. Remote monitoring

Monitoring the operation of mini-grid systems is crucial in the operationalisation of the system. It actually represents one of the critical areas and actions to track the performance and efficiency and effectiveness of the system. Digital technologies offer the possibility today to remotely monitor mini-grid systems operations. Indeed, it is possible to control and manage in real-time the different parameters of the of the transmission and distribution networks/systems. indeed, sensors can be installed at different points in the systems to collect data and detect anomalies in the system that can require immediate action or not helps in the planning of the maintenance activities planning (IASS 2019). Several mini-grids on the continent are adopting this digital technology application in their mini-grid to improve the resource utilization by remotely identifying and troubleshooting problems in the system with the support of local staff. Several mini-grid operators East Africa are implementing the technologies with limited physical onsite presence using web-based remote monitoring platforms. These solutions facilitate data capture of key system performance metrics that can constitute the basis for the analysis and further research to identify and support the development of improved systems' design and standards while providing evidence for the development of appropriate policy and strategy to develop the sector. Besides the use of remote monitoring to capture performance data and implement optimal maintenance plans and strategies for the long lasting of the mini-grid systems, they can also be used to capture non-system data in remote area such as societal, economic, environmental data to monitor the socio-economic and environmental impacts of the system within the beneficiary community (Dauenhauer et al. 2013). The remote monitoring systems often encompasses two main components: - the local Remote Stations collecting data from the different sensors in the different sub-stations through nodes with ZigBee module; and transferring the latter to the Central Monitoring System through GPRS protocols; - the Central Monitoring System that aggregates all the information received from the RSs and will process them for appropriate decision. It encompasses the monitoring personnel to take/implement actions when needed, the server to receive, store and display information; and the internet to allow access to the data/information from everywhere (Dauenhauer et al. 2013). Remote Monitoring systems are also often built on new Advanced Metering Infrastructures such as smart meters to collect relevant data on the system performance and transmit them to the central monitoring systems. This simplistic architecture of remote monitoring systems can be further adjusted to include smart meters, data analysis tool an operational intelligence as per the below Figure.

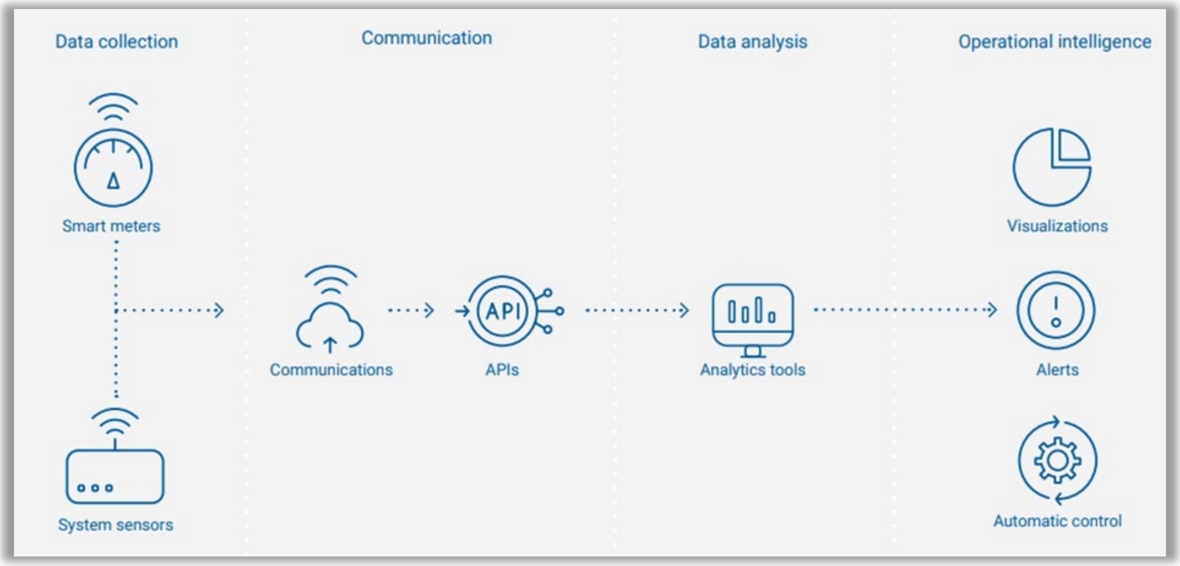


Figure 10: Illustrative setup of remote monitoring Source: TFE Energy (2020)

3.1.1.4. *SCADA / Internet of things*

SCADA stands for Supervisory Control and Data Acquisition and is a system for remote monitoring and control that operates with coded signals over communication channels (using typically one communication channel per remote station)" (Kayem et al. 2018). As a real-time control and data acquisition system is a large-scale remote management system SCADA can analyse a huge number of telemetry readings in real time and handle technical installations from a distance. It is made up of hardware, controllers, networks, and communications, as well as a database, input/output management software, and a human-machine interface. The field information collected by the SCADA system is centralized on a central unit enabling the operator to operate all or a portion of the actuators in a typically large installation. In addition, there is a human-machine interface that displays data to a human operator and enables him to monitor and manage operations, a computerized monitoring and control system that collects process data and sends orders to the processes; a remote terminal device that connects the sensors, converts the signals to digital data streams, and sends the digital data to the monitoring system; and a communication network connecting the supervisory and control system to the terminal components including a variety of analytic tool (Actors solutions 2022)

The Internet was created to link and transport data between computers in its early stages. The Internet became a network that also enabled constant communication between individuals with the introduction of smartphones (technically small computers). As electronics and information technology progressed, "things" that are not computer or communication devices by nature began to be linked to the Internet. The phrase "Internet of Things" first appeared in print in 2005, when the International Telecommunication Union released a paper titled "Internet of Things," which described the emergence of IoT.

It was the beginning of the change. The Internet of Things (IoT) boosted global interconnection to new heights, allowing for previously unimaginable technical, social, and economic advancements. One of the primary technologies fuelling the fourth industrial revolution is the Internet of Things. IoT has continued to expand at an exponential pace for more than a decade. In 2016, there were roughly 17.6 billion devices linked to the Internet, with 11.2 (64%) being traditional devices like smartphones and laptops and 6.4 (36%) being other devices, or "things," such as appliances, meters. Several projections were made regarding the number of interconnected objects (devices and things) by 2020 and included (Nordrum 2016), (Lucero 2016). the overall analysis of these trends highlights a constant trend in the increase in interconnected things/devices for the coming years. The energy and mini-grid sector will like many other sectors be impacted as well by the development of the IoTs. Indeed, IoT are changing the way mini-grid have been operating. They offer the possibility to digitalise a number of operations related to monitoring and maintenance of the systems with the overarching aim to reduce the operational costs and ensure efficient delivery of the supply. Their architecture and associated environment allow also the collection of customers behaviours that allow the improvement of the services, and the design of services that are customised and dedicated to meet customers' needs; and offer the possibility to remotely controlled some devices and equipment for the smooth operation and response to problem that might occur on the system (Mini-Grid Partnership, 2020).

3.1.1.5. Demand forecast

Load forecasting is the prediction of future loads, which is crucial in the energy management system and improved power system planning. A considerable number of studies on precise short-term load forecasting have been published in recent years owing to its influence on power system reliability and economics. It guarantees the smooth running of the power system, resulting in uninterrupted power delivery to the customer (Methaprayoon et al. 2003) Accurate load forecasting may make power system operations such as scheduling, maintenance, tariff rate modification, and contract assessment much easier. On the basis of realistic load forecasts, energy policy decisions may be made. Various power management system choices, such as power system operation, maintenance, and planning, are based on load forecasts (Kamel and Baharudin 2007). While the initial costs (CAPEX14) of a mini-grid system/project can be optimised using accurate load forecast, the entire system planning can record additional savings of financial resources.

Load forecasting is significantly influenced by individual load consumption. Indeed, in previous years, most efforts were focused on short-term load forecasting. According to a survey of the literature, a considerable number of studies have been published on short term load forecasting for various load situations, load prediction types, and their application for a reliable and efficient energy management system. Seasonal load prediction scenarios are frequently shown as short-term load forecasting case studies to examine forecast model performance and utility perception for many users. The distribution of generating resources, operational restrictions, environmental and equipment use constraints may all be determined with the aid of reliable load forecasting (Rahman and Hazim 1993).

[14] Capital Expenditure

Load forecasting are crucial for the optimal operation of the systems. In systems including energy storage, they can be used to identify the appropriate time for the release of water reservoirs and plan hydropower generation units' schedules when needed. Additionally, they can help securing mini-grid infrastructures, by determining critically the ideal system operating conditions, while informing decision concerning the preparation or not of the system for future load conditions as well as remedial measures (Raza and Khosravic 2015).

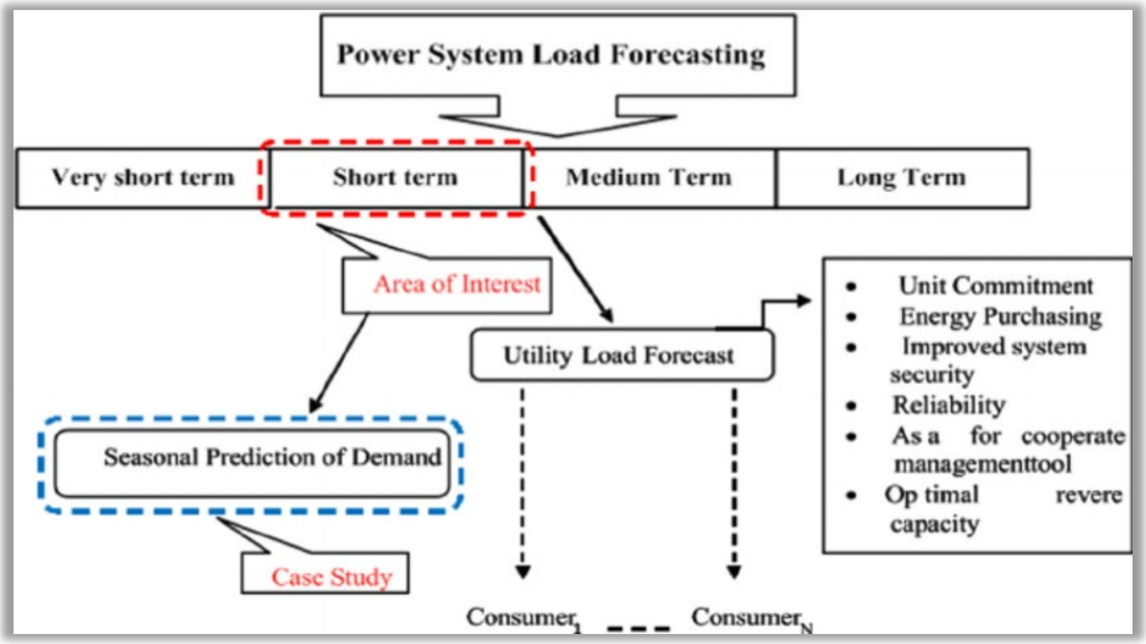


Figure 11: Types of load forecasting and application of short-term load forecasting. Source: Raza and Khosravic (2015)

Load forecasting can further be used in power system economic dispatch and dependability. The power system's dependability is significantly affected by sudden changes in load demand. If the load demand is underestimated, for example, the system may have a power supply shortage. As a result, managing overload circumstances and overall power system quality is tough (Huang and Shih 2003).

While load forecasting represents a very important element in the optimization of the operation of the mini-grid, upstream, the load data should be extensively investigated and the dynamics should be properly understood in order to create a suitable prediction model. The relevant procedures on load data should be conducted based on the behaviour and fluctuation in load data to provide excellent prediction results. One of the data treatment procedures that may be used on the basis of load profile analysis is data pre-processing or data normalization. The network's input data may be divided into multiple clusters depending on their properties, potentially improving network performance. An analysis of the load data can lead to the establishment of load trends basis for the further development of policy decisions in the locality. This can lead as reported in (Drezga and Rahman 1998) to a huge difference between load patterns in a geographical region depending on consumption habits driven by meteorological circumstances/changes due to seasons.

This approach is useful for planning and scheduling power systems. Indeed, in several parts of the world such as Europe and Asia, we can observe a rise in temperature depending on different seasons (winter through summer) that yield to a load demand very high in the summer and comparatively low in the winter. This is mainly due to the cyclical pattern of consumers load that varies cyclically during the 24 hours of the day, based on the customers' daily and regular activities which depends on the time of day (as working hours, school hours, and midnight). The pattern of load demand may be seen repeated throughout the week with variations in peak load demand.

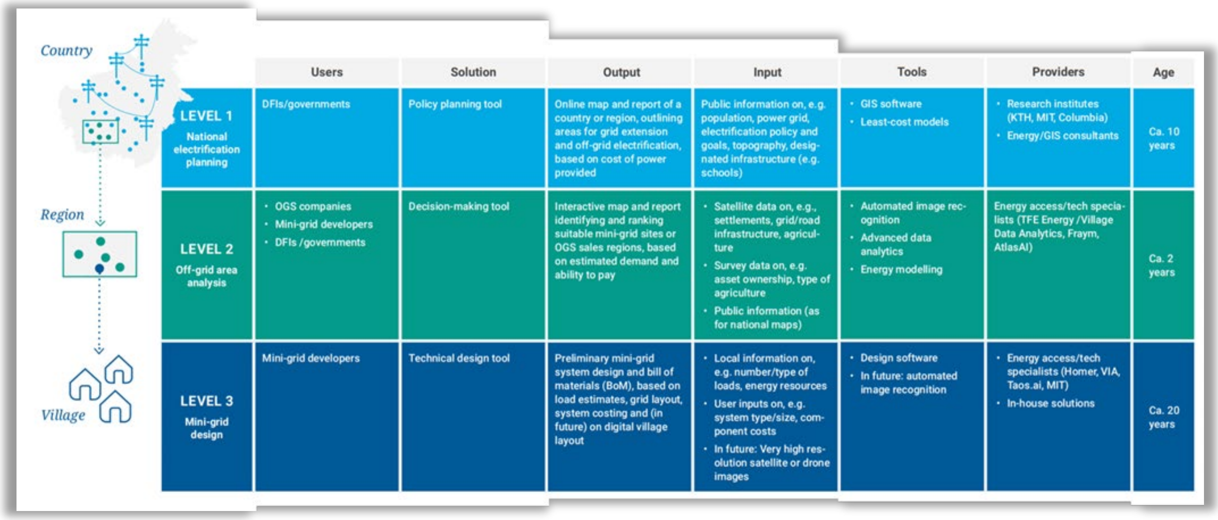
3.1.2. Planning and operational functionalities

3.1.2.1. Digital planning and design

Digital planning tools can support electrification strategies and operations accelerating them, improve their accuracy and reducing uncertainties and, ultimately, risks. Governments and development finance organizations in the energy access sector already start using digital planning to identify least-cost electrification strategies and develop attractive tenders. Mini-grid developers can find suitable sites more quickly and reliably, and they can create initial system layouts and cost estimates. OGS (Off-grid solar) product companies can identify attractive sales regions, cross-check customer information and better plan distribution channels. Planning tools are rapidly gaining in relevance as the market seeks to scale and many stakeholders are shifting from anecdotal or opportunistic approaches to data-driven and strategic decision-making.

The digital planning tool chain, represented in Figure 12 below evolved from the mini-grid industry where the considerable expenditures put into stationary infrastructure need a certain level of planning. Finding the least cost electrification option, the correct location for a mini-grid or developing the most cost-effective system configuration vitally effects the financial feasibility of the venture.

Currently, the tool chain is implemented infrequently and by diverse stakeholders. Governments and development financing institutions (DFIs) utilize increasingly least-cost maps for planning electrification, although they are not currently accessible for every nation with low energy access rates at acceptable quality. Site identification technologies for bidding support are just starting to be deployed. Similarly, mini-grid developers and OGS businesses are not yet making full use of the toolchain. Planning tools are increasingly rising in significance as the industry attempts to scale full utilization of the toolchain. Most established is the usage of technical design software for mini-grids. These are either in-house or third-party solutions, such as HOMER For location identification, most still work manually using Google Earth. The work is nearly often done by electrical firms in-house. Advanced site evaluation technologies, such as Village Data Analytics are just now accessible in the market. However, as the OGS and mini-grid industries expand and players are eager to speed project development or sales, or push into new regions, site assessment tools that give an analysis of potential locations become more relevant. They assist mini-grid firms better discover appropriate locations and OGS companies identify possible consumers and design efficient sales and supply plans.



	Users	Solution	Output	Input	Tools	Providers	Age
LEVEL 1 National electrification planning	DFIs/governments	Policy planning tool	Online map and report of a country or region, outlining areas for grid extension and off-grid electrification, based on cost of power provided	Public information on, e.g. population, power grid, electrification policy and goals, topography, designated infrastructure (e.g. schools)	• GIS software • Least-cost models	• Research institutes (KTH, MIT, Columbia) • Energy/GIS consultants	Ca. 10 years
LEVEL 2 Off-grid area analysis	• OGS companies • Mini-grid developers • DFIs /governments	Decision-making tool	Interactive map and report identifying and ranking suitable mini-grid sites or OGS sales regions, based on estimated demand and ability to pay	• Satellite data on, e.g., settlements, grid/road infrastructure, agriculture • Survey data on, e.g. asset ownership, type of agriculture • Public information (as for national maps)	• Automated image recognition • Advanced data analytics • Energy modelling	Energy access/tech specialists (TFE Energy /Village Data Analytics, Fraym, AtlasAI)	Ca. 2 years
LEVEL 3 Mini-grid design	Mini-grid developers	Technical design tool	Preliminary mini-grid system design and bill of materials (BoM), based on load estimates, grid layout, system costing and (in future) on digital village layout	• Local information on, e.g. number/type of loads, energy resources • User inputs on, e.g. system type/size, component costs • In future: Very high resolution satellite or drone images	• Design software • In future: automated image recognition	• Energy access/tech specialists (Homer, VIA, Taos.ai, MIT) • In-house solutions	Ca. 20 years

Figure 12: The digital planning tool chain. Source: TFE Energy (2020)

For mini-grids, a design software has been among the first digital tools to emerge in the energy access sector and is extensively used today such as HOMER Energy[15]. It was first created by the US National Renewable Energy Laboratory under the Village Power initiative in the 1990s. Advances in processing power and architectures, such as parallel computing, have made design software even more complex and faster Energy system design software requires data on sites and consumers, i.e., potential consumption, customer groups, productive loads, number and location of households. These may also show restraints on the location of the generating asset as well as the distribution grid. Another source of information on building footprints and kind is the Humanitarian OpenStreetMap project, which has digitally mapped significant areas in East Africa and beyond. In addition, firms such as Development Maps provide a digitization service of dwellings based on Google Earth images. Taos.ai, an Engie spin-off, exploited drone photos of remote settlements to develop mini-grid distribution layouts.

3.1.2.2. Digital payment

Digital payments are any non-cash payments, in which the payment is made electronically. One sort of digital payment is mobile money. This revolutionary technology has emerged as

[15] https://www.homerenergy.com/

a dominant payment platform in many developing countries with over 866 million registered accounts (143 million were added in 2018 alone) and transactions over $1.3 billion made every day (GSM Association, 2019). Energy access providers have swiftly incorporated mobile money into their business models, since it drastically decreases their operational costs and risks associated with handling cash. Oftentimes, it is the only form of payment they give to clients. In the nations where mobile money is not widely accessible (for instance, in parts of francophone West Africa, in Nigeria or in Ethiopia), it substantially limits the expansion of electrification enterprises. Digital payments have been utilized by energy access firms - OGS companies – for more than a decade and have grown ever more significant, as the OGS industry shifts towards selling bigger, more costly devices that enable higher tier energy access (World Bank and GOGLA 2018). If cash is utilized as the payment method, the consumer has to routinely connect with a physical vendor agent. These have become the major payment mechanism for PAYGO (Pay-as-you-go). The relevance of digital payments to the OGS business model is evident in investment patterns between 2012 and 2017, when PAYGO businesses got 80 % of the financing in the OGS market a total of $773 million (World Bank and GOGLA 2018).

In 2018, 68 % of PAYGO firms were vertically integrated, with more than half creating their own digital payment platforms at expenses of $1-10 millions. Today, digital experts such as Solaris Off-grid, Mobisol and ANGAZA provide digital payment solutions for their services. As shown in the figure 13 below, between 2012 and 2018, mobile money grew from 135 million to 860 million users. Sub-Saharan Africa has the highest numbers, followed by South Asia showing a growing interest of the technologies including in the energy sector and sub-sectors (World Bank and GOGLA 2018).

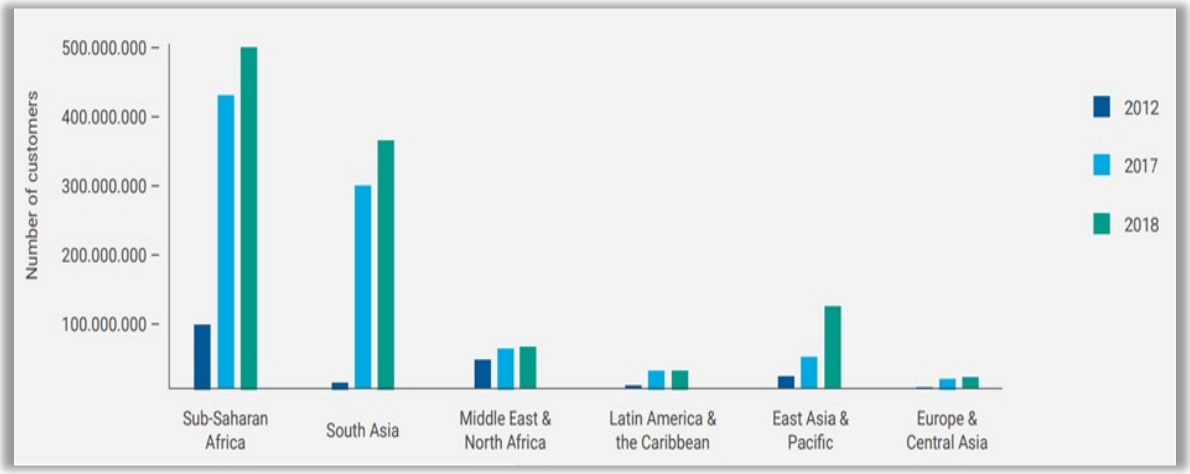


Figure 13: Mobile money users by region. Source: World Bank and GOGLA (2018).

Furthermore, the new development of blockchain technologies offer the opportunity to develop new energy market with specific focus on energy trading. Indeed, unlike conventional energy trading which is unidirectional, blockchain technology through peer-2-peer energy trading can allow for trading between the different prosumers and consumers in the mini-grid environment. With its specific functionality of shared platform for information and transactions, it facilitates transaction amongst the different members of the markets with a high level of transparency. This is done thorough an internet-enabled smart meters that collects and documents all electricity generation and real-time demand, and the different transactions executed by the market participants (GIZ, 2020).

3.1.2.3. Digital finance

The financing of mini-grids systems has been one of the critical challenges faced by developers in the sector. Indeed, often times, mini-grid project developers face challenges in mobilising sufficient financial resources due to high investments' risk involved in the project and the ability to raise capital to finance the projects. IASS (2019) highlights the role digital technologies could play in de-risking mini-grid projects. Indeed, they offer more transparency in the different processes from project development to assessment, thanks to the availability of data through numerous means that allow access to different information from generation to consumption and at various stages of the project, dispelling thus, doubts from investors regarding the project. They further enable the development of platforms to raise funds in order to finance mini-grids projects through crowd-funding which allows the use of lesser amounts of capital from a large number of individuals to finance a new business venture (Investopedia 2021). The process is almost exclusively online. Its application to the mini-grids has been limited with a higher perceived risk due to discrepancy between the shorter-term of loans in crowdfunding versus the long-term debt required in mini-grid. Nevertheless, several crowdfunding platforms have been developed to fund mini-grid projects in Africa and include Bettervest[16] trough which projects in Nigeria and Madagascar received funding (Green Minigrid Help Desk 2020). This fundraising approach can further be used in the case of revenues-based financing where the mini-grid project offers clear exit within a short-term. In addition, projects have the possibility nowadays to access further actors in the financial arena through project aggregations, which allow different projects of small sizes to come together to increase their Capital expenditure and thus access some important fundings and stakeholders. Several companies on the continent have implemented this approach to raising funding to cover the capital costs for the implementation of mini-grid projects including renewable based projects such solar PV-based mini-grids. Furthermore, the emergence of distributed ledger technologies is disrupting the financing methods of mini-gird and off-grid electrification project general on the continent but also in other parts of the world. Indeed, mini-grid projects can nowadays be financed by means of cryptocurrency(ies) and blockchain technology. Though cryptocurrency, tokens are generated and sold on a trading platform to fund electrification projects. This process allows the contribution of a wider community in the fundraising process while, offering the possibility to the community to own asset of mini-grid asset and benefit from the sales throughout the project life time (Bungane 2018). Although, the concept seems very relevant for the African context with its capacity to open mini-grid projects to communities around the world, the enabling environment framing the deployment of the activities is still to be established for a wider application on the continent. The implementation of the concept is so far still very limited on the continent though, with applications in few countries including South Africa, and Kenya[17]. The emergence of Blockchain technology described as a protocol that eliminates intermediaries in a transaction

Bettervest: [16] a German peer-to-peer business lending platform
The SunExchange[17]: https://thesunexchange.com/

by open an era of more auditable encrypted ledger that can record energy consumption and credits history and allow trading of electricity among consumers (International Telecommunication Union, 2020). In addition, through the enabling resp. development of smart contracts, blockchain application in mini-grid allows the transparent tracking/monitoring of energy consumption and generation by the means of peer-2-peer energy sharing management tool (Zhang et al. 2017). On the continent, several countries such as Ghana, Kenya are exploring the application potential in local mini-grid including in combination with artificial intelligence to define dynamic electricity prices of electricity (Finke et al. 2022).

3.1.2.4. Digital operation and maintenance

There are very few sectors in the world today that do not employ digital technologies to streamline their operations in some manner. Examples vary from commonly used accounting inventory and CRM (Customer relationship management) applications, to more specialized ones, like as contact centres and sales force management apps, and to highly complex analysis of user data to properly target advertising goods and services. These issues fall roughly into two categories: the operation and optimization of technology in distant places and the administration of a widely scattered frequently impoverished client base.

The first difficulty has been met utilizing remote monitoring technologies. The second problem dealing with distant and frequently unbanked clients has been addressed with the introduction of GSM and internet-enabled smart meters and PAYGO switches. The development of digital operations tools has grown through three stages. Starting in 2010, first movers into the rural electrification market, like Bboxx, Earth Spark International, access: energy and Devergy, were forced to develop their own proprietary digital operations solutions since there was nothing available on the market to meet their specific needs. This first occurred in the mini-grid sector with access: energy and Earth Spark International growing out of smart meter experts SteamaCo and Spark Meter, respectively. More recently, digital operations professionals, such as AMMP Technologies and Fern Tech joined the market. With these solutions, clients may get significant operational and consumer data from a vast portfolio of projects (TFE Energy 2020).

3.2. Smart grids

3.2.1. Definition and general concepts

3.2.1.1. Conventional grids versus smart grids

In conventional power grids, power flows are one way only from production to customers and control and monitoring elements are excluded and not implemented on grids. There are only passive components, such as transformers and manually controlled switches etc. included in traditional power systems.

However, the world has been changing and the energy system along with it. During the recent year (over the past ten years), power distribution networks are heading toward smart grids (SG), globally. Global PV revolution and following energy transition is happening. As part of these energy storage solutions and battery chemistries and technologies as well as energy markets are developing rapidly. Adding renewable-energy-based production in distributed manner to the grids and the following bi-directional power flows in grids has generated a need to add new functionalities, such as automatic meter reading, demand side management, demand response and load control, IoT applications has arisen. With these new features the grid can be supervised and operated in controlled manner enhancing and enabling also the possibility to operate the grid in flexible and more importantly in electric safety way. This has also become a mandatory characteristic to prevent undesired events such as over voltages and currents. Adding new sensors to the grids the amount of data is exploding. Accordingly, the number of data transactions is to be increased exponentially. Communications and connectivity solutions together with data management systems have become essential parts of grids. Thus, there needs to be seamless integration of power and information and communication technology (ICT) systems in grids as between grids and between cloud where the services are run. This change brings both challenges and opportunities. The grids are becoming more complex, there are cyber security issues arisen (many 'holes' to the critical infra), but it is also a place to introduce new digital services.

Smart grids are created when disruptive technologies such as wind and solar generation, that is, weather dependent energy sources, are (already are) mass-production-based technologies and roll out to the grids. Same applies to energy storages, those introduce new component in power system, a source for flexibility and running grids in islanded mode (in grid-connected cases), and introducing a self-sufficient mini and microgrids both in on-grid and off-grid areas. The third element is digitalization. As everything becomes connected to internet, and accordingly new applications and opportunities are introduced and enabling running grids in flexible and cost and energy efficient ways, as well as through new and easy-to-use digital services connecting and engaging consumers and prosumers to become active element of energy markets.

In Europe, the transition is driven mainly by the societal needs and the EU energy policy objectives. Novel smart grids in Europe should constitute a competitive and liberalized environment with the energy producers, micro-generation facilities and modern electricity distribution systems. There have been big trends in development of power systems towards smart grids, which have even become more essential now during the (bad) news from COP26; taken actions to cut down carbon emissions are not sufficient to achieve the target, that is, to stay below 1.5 Celsius in temperature increment. Greenhouse gas (GHG) emissions must be decreased, carbon capture solutions further developed and scaled up, and carbon compensation and trending system further deployed. Moreover, improvement in the EU's overall energy efficiency is set goals, and growth in the share of energy obtained from renewable energy sources must be even further accelerated.

These objectives have partly changed the electricity production scheme. Today the power flow is not anymore only from the centralized primary power plants to the customers, while the number of distributed generation (DG) units or decentralized connections of renewable energy technologies, such as wind turbines, and photovoltaic cells in the consumers at the ends of electricity distribution systems has increased. In addition, with battery energy storages (BES), which are becoming more common in modern smart grids, the electrical power can be stored for the electricity blackout, to sustain the distribution grids during faults and in island modes. Furthermore, those can be used as a sources and assets in energy markets while driving the grids in cost effective manner. To control the power flow in the grids, and provide uninterrupted energy supply to the customers, ICT systems on the distribution grids have become a necessity. Information about the status of the distribution grid, behavior of the customers, and statuses of the DG and BES units in the grid, are needed to be collected to the master of the grid and to the remote data bases of the distribution and transmission system operators (DSO, TSO). With this information, the efficiency, reliability, and the flexibility of the electricity production and distribution can be improved, as one major focuses of the SG principles. Furthermore, the energy consumption peaks can be equalized by the DGs and BESs. The deep integration of ICT systems with power distribution grids is a main cornerstone in implementing SGs. A second foundation stone are the smart functionalities implemented on the intelligent devices in the grids exploiting the available ICT. The electrical energy consumption and production data from the customers are collected and analyzed, and this information is used for instance for demand side management (DSM). DSM is essential for optimizing the power consumption, and minimizing the cost of power supply in SGs. Further, monitoring and controlling the grids to provide continuous and reliable power distribution for the customers is needed.

3.2.1.2. Characteristics of a smart grid

In Smart Grids (SG), intelligent electronic devices (IEDs) play a key role. IEDs include actuators, relays, IoT sensors, and embedded PCs (EPC), which take care of running the power system safely and also energy and cost efficiently by the set parameters and based on input data from different sources, including weather, grid normal operation etc. As stated above, there needs to be data management system locally in grid layer and also one in cloud systems with reliable connection link between these.

3.2.1.3. Functions of a smart grid

Functions of SGs include monitoring and controlling schemes and applications, which are essential when the power system is operated and run in most efficient way; taking into account both the energy efficiency; run the system in most optimal operating point: monitoring, metering, control, autonomous locally and remotely from cloud run grid automation, and supervision.

3.2.1.4. Structure of a smart grid

Smart grid consists of 1) power systems elements including production, distributed generation units, energy storages, transformers, power electronics and converters, and customer with their loads, and 2) those measuring, monitoring and sensoring elements, including IoT sensors, automatic meters with digital services and platforms for customers and end users, active actuators and devices, circuit breakers, transformer and grid automation solutions. Besides these there are the local and remote data bases and control and monitoring signals and data exchange between all the active devices. To enable data transmission between different nodes in the grid, communication networks and solutions needs to be in the picture.

3.2.1.5. Conceptual model of a smart grid

The conceptual model of a smart grid is depicted in Figure 14 below.

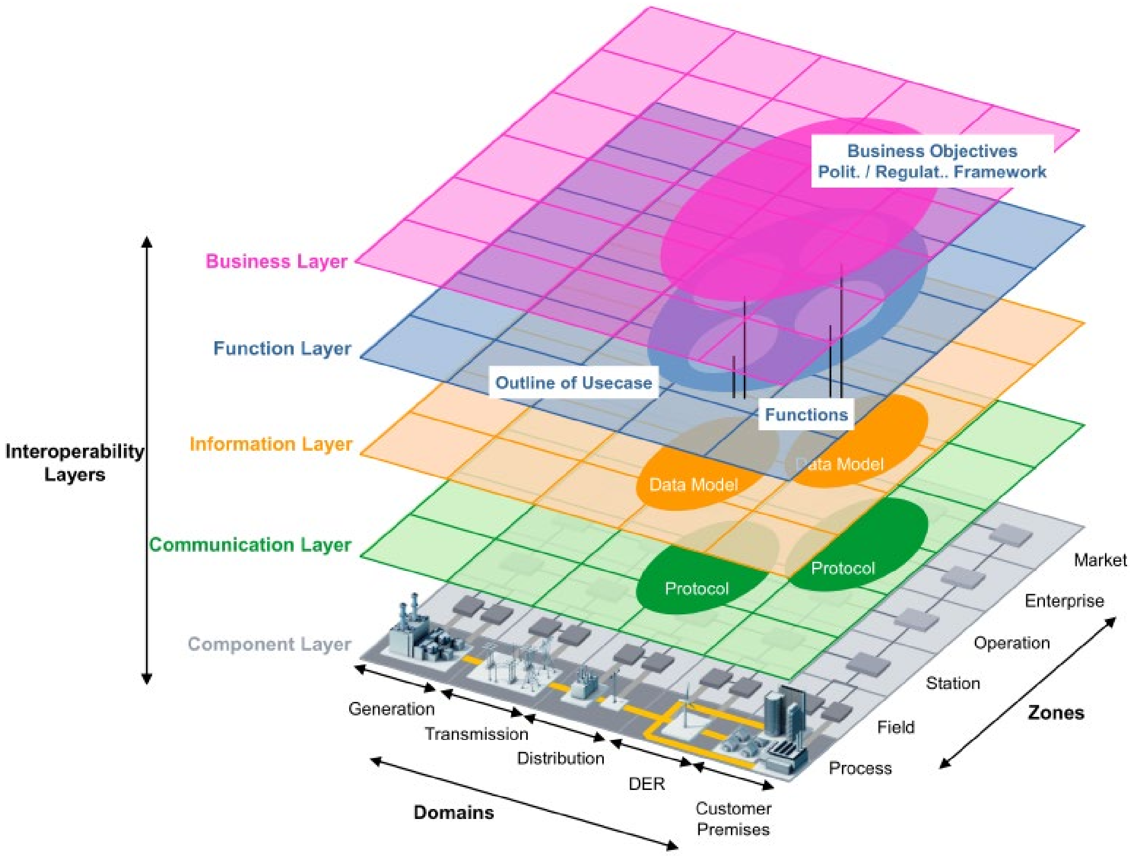


Figure 14: The Smart Grid Architecture Model (SGAM) Framework (CEN 2012).

In this African mini-grids context, the SGAM model needs to be tuned accordingly to fit to the surroundings. In this context the focus is on addressing the livelihood-improving green electrification and digital inclusion with an “infrastructural stack” in mind, aligned with the recently presented Smart Grid Architecture Model (SGAM) (see Figure 14), which has been applied for instance on studying the microgrid management systems in (Sirvio et al. 2020).

A microgrid provides a technical platform for an energy communities concept, enabling for instance peer-to-peer (P2P) trading. This concept has been proposed also to African communities (Kusakana 2019).

However, as illustrated in Sousa et al. 2019, there are research needs especially in the quantifying the benefits and in human dimension modelling of the consumers related to P2P markets. In order to deliver livelihood outcomes (business and function layers), the introduction of digital services (communication and information layers) requires electricity. The setup and installation of the baseline technical system (component layer) requires coordinated construction activities with multiple complexities.

Sustainable livelihoods framework (Scoones 1998) introduces an approach that recognizes the existing capacities that people have even in vulnerable surroundings. By taking such capacities into account, it will be possible to formulate new approaches and ways of introducing modernizing infrastructures, such as electricity, to previously underserved places and surroundings. Fresh approaches with more agile and scalable processes that take into account the socio-techno-economical and contextual aspects can benefit the ramp-up of sustainable electrification and introduction of digital infrastructure.

3.2.2. Components of a smart grid

3.2.2.1. Energy storage component

Energy storage component besides renewable-energy-based electricity production is the key element in smart grids. In off-grid mini-grid context or even in grid-connected cases, it introduces the element providing uninterrupted and reliable electricity power supply to customers and at the highest priority. This needs seamless communication between different elements of the grid, especially between production unit(s), and consumption, that is, loads, and the battery energy storage system state of charge.

So far, the main chemistry in battery energy storages used in grids has been lead acid, which has several disadvantages; It is heavy, those usable energy capacity and cycling depth are roughly 50% (and accordingly dead weight is roughly 50%), it requires special casing due to electric sparks, has short calendar age and even shorter usage age, has limited temperature operation area. Thanks to battery development mainly in EV industry, the prices of Li-ion batteries have been rather steeply decreasing still. For instance, Lithium Iron Phosphate (LiFePO4) is one of the most suitable battery chemistries to be used in power systems. Those cycling depth are around 80%, those can withstand wider temperature range and loading of the battery (discharge), are lighter and does require less space, cycle life is several years longer etc. The prices of Li-ion batteries are still higher than that of lead-acid batteries, but taking into account the longer life-time of Li-ion batteries the initial investment pays back and the total costs during the battery lifetime are lower than with lead acid batteries. The challenge with li-ion batteries is the recycling and reusing the raw materials used in the batteries. Fortunately, this is global challenge and new solutions for recycling are searched and studied actively.

3.2.2.2. Monitoring and control technology component

Monitoring and control technology components in African mini-grid context should be open-access-based till some extent, in the level of software platform on which different algorithms and services are implemented. Moreover, the affordability but also reliability of the applied solutions for supervision needs to be considered. The control and monitoring architecture for the energy management of mini grids needs to compatible between different layers in the power system architecture, which include transmission and distribution systems, local and national electricity markets depending whether it is off-grid or on-grid solution, local measurement and control and customer premises and load profiles. Between these layers, there need to be links and feedback routes, as the mini-grid is to be run in most reliable and cost and energy efficient ways taking into account the power system as assets to be taken care of to guarantee long and maximum life time of the system. So, it is a tradeoff between that and quality of service in electricity power delivery. Thus, this becomes a parameter in mini grid business model. The compatibility is essential element also from the sake of modularity and scalability of the mini-grid power system; scalability with possible load demand increment.

In principle there is one main server or controller in the grid layer, a master device or computer that takes care of the local supervision and control of the grid operations. Besides the master unit there are end nodes in each grid element and unit that are to be controlled and monitored. Besides these there are communication networks that interconnects all these together.

3.2.3. Communications and network

Communication networks in smart mini grid context can be categorized in several network layers.

3.2.3.1. Home Access network (HAN)

Home area network as the name says cover the communication network and devices within the network at customer premises, and is used for instance in controlling the customer loads and monitoring the DGs. Those include A/C, lights, heating. Some unlicensed frequencies and IoT solutions such as Wi-Fi could be used as data communications in HAN. The attention must be put in interoperability and further in cyber security as the HANs are to be connected seamlessly to other communication networks for fluent operation of the power system.

3.2.3.2. Neighbourhood area network (NAN)

Neighborhood area network covers e.g., few houses close by in a same community feed from the same mini grid power system. Depending on how close the households are from each other, Wi-Fi is one viable and low-cost solution to deliver access, data and connections between different appliances and applications.

3.2.3.3. Local area network (LAN)

Local area network is formed for instance on the layer covering all the active appliances monitored sensors and controllable devices. The other parameter besides the network coverage area to be taken into account is the time scales and windows that different applications and devices require and can deliver, e.g., some critical grid protection devices require low latencies but low data to be transferred, when again e.g., energy meters, are not that time critical at all depending on the energy usage data collection, if that is not used to operate the mini grid in event-based manner.

One potential communication network solution for LAN in mini grids is wireless mobile networks, which are covered in some of the places and locations. The same network could be used for IoT services related to mini grid operation and also to deliver voice and data with internet access to the end user.

3.2.3.4. Wide area networks (WAN)

WAN includes the backhaul connectivity of the whole mini grid and connects it to the cloud system, data bases and remote services. Depending on the availability and coverage of existing mobile network, the other alternative for backhaul connectivity in areas outside of mobile network coverage area can be microwave links which most cases require line of site (LoS) between the microwave end nodes. Fiber network would be the most optimal solution as provides high speed reliable connection, but is not available in rural places. Satellite connection is also an alternative for backhaul connectivity, but limiting element is the high cost of the connection to internet and cloud services.

3.2.3.5. Cloud architecture of smart grid

So far majority of the smart grid services are run cloud based, but this is not the sustainable nor feasible solution taking into account the data analysis, quick decision-making requirement in crucial applications (grid protection). Moreover, data transmission of huge data sets or raw data from grids to cloud servers requires lot of energy, thus being not at all sustainable solution. Thus, the transition has been that more and more functionalities are run on the grid level in local server and only the necessary data is delivered to cloud in raw format, but as much as possible data parameters what needs to be relayed between grid main controller and could systems and databases are transferred. This is the feature that is introduced in private 4G LTE networks. There is edge core PC taking care of edge computing; local services are run and delivered to the end devices and customers independently on the backhaul connectivity existence or availability. This is crucial direction as the dependency on communication network availability cannot be the limiting factor when reliable power delivery is to be served and delivered. As an example, it is not good case, if the mini grid is shut down when the mobile network used for data communication between grid main controller and cloud is down due to some reason that has nothing to do with the mini grid operation.

3.2.4. Data and protocols

ICT is an essential part of modern Smart Grids. The data transmission is required for metering, control, and energy management functionality. There are several data transmission protocols used in the Smart Grids.

3.2.4.1. Open smart grid protocol

Open Smart Grid Protocol (OSGP) is a smart metering/smart grid communication protocol. The protocol is based on open system interconnection (OSI) model and includes three main levels: Application (ETSI TS 104 001); Network and Physical. It has a request/response type of data exchange.

- The application layer (ETSI TS 104 001) is an updated version of ETSI GS OSG 001, which provides table-oriented data storage and has enhanced security features, including AES 128 encryption.
- The network layer utilizes ISO/IEC 14908 control networking standard, which is optimized for reliable, scalable, and efficient control networking applications. It also allows to achieve high performance without obligatory high bandwidth.
- The physical layer uses ETSI TS 103 908 (PowerLine Telecommunications), which defines a high-performance narrowband powerline channel for control networking in the smart grid.

One of the disadvantages of OSGP is incompatibility with IoT protocols such as e Constrained Application Protocol (CoAP), conventionally used in IoT. However, this challenge can be solved with the design of a software interface that provides integration between OSGP and CoAP.

3.2.4.2. PRIME protocol

PRIME protocol is a public, open, power line communication (PLC) based, non-proprietary telecommunication standard for the needs of smart grids. It defines two types of nodes: Base Node and Service node. Base node is a core of the system, which is referred to data concentrator and takes responsibility for the control of the subnetwork including all Service nodes. A service node is a node that takes part in the subnetwork. PRIME protocol contains three layers:

- Convergence Layer, which classifies network traffic based on its MAC layer.
- Media Access Control Layer (MAC), which provides bandwidth, access, topology resolution, and connection management.
- Physical layer, which exchanges data packets between nodes, applying OFDM modulation.

In power line communication (PLC), power lines are used for data transmission channel and data signals and packets are coupled and relayed between end nodes and master devices connected to grids. PLC is used mainly for power grid applications; monitoring and control and AMR measurement data gathering, that is, IoT in transmission and distribution networks as well as in multimedia media applications inside customer premise utilizing the in-house power lines. Thus, PLC is data communication solution both in LAN, NAN and HAN layers.

3.2.4.3. DLMS/COSEM protocol

DLMS/COSEM protocol is one of the most used protocols for the implementation of advanced metering infrastructures. The protocol defines client-server architecture, where a smart meter acts as a server and the device as a client. Such an approach allows a smart meter to send information directly to a client device as alarms and configuration data. IEC 62056, which is a version of the DLMS/COSEM protocol is considered as an international standard and is actively maintained. The protocol supports several security features. Message protection – use of cryptographic protection to the Application Protocol Data Units (APDU), ensuring the confidentiality and integrity of the information transmitted. Role-based authentication – allows establishing per authentication of data. There are three levels:

- Low level: no authentication required.
- Medium level: password is sent in clear text, and only the client device needs to be authenticated.
- High level: mutual authentication is required. Both a client and a server need to be authenticated, using cryptographic primitives.

3.2.4.4. IEC61850

IEC61850 is a standard originally used at electrical substation and for substation automation. It defines three main protocols:

- Manufacturing Message Specification (MMS) – is a TCP protocol, which has client/server architecture and is used for the transmission of not time-critical control and management data between SCADA and Intelligent electronic devices IEDs.
- Generic Object-Oriented Substation Event (GOOSE) – is a UDP protocol, which has subscriber/publisher architecture and is used for the exchange of time-critical data needed for the control and protection functionality.
- Sampled Values (SV) – is a UDP protocol, which has subscriber/publisher architecture and is used for the data transmission between measuring devices and IEDs.

The initial version of the standard defined data transmission applying GOOSE and SV protocols only within LAN, and a message frame didn't include any security field. In the second edition of IEC61850 published in 2012, there is an introduction of extended versions of protocols named Routable (R)-SV and R-GOOSE, that allow the transmission of the data over WAN and introduce encryption to the message date frame.

Therefore, IEC61850 can be a feasible alternative to existing Smart Grid protocols, allowing better integration of a smart grid into the power system (Demidov et al. 2022).

4. Digital technologies development in SSA

4.1. Background

4.1.1. ICT development on the continent

Since the late 1990s national ICT strategies exist in many African countries. These strategies are particularly centered 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. More recently, 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. It has even become central at continental level with the development of a continental digital transformation strategy – The AU's Digital Transformation Strategy 2020-203018 given its potential for socio-economic development of the continent. The strategy builds on several strengths identified such as mobile phone availability and affordability on the continent, sustainable growth of the internet market, the development of policies and identification of different barriers for the harmonization of the regulatory framework across countries; and an increased momentum on the topic of digitalization (African Union Commission 2020).

Besides, acknowledging the potential of internet and digital services in improving economic and social conditions of the populations, several African countries have started he design and implementation of policies and strategies to harness to full potential of ICT and digitalization especially given its impacts on socioeconomic and development sectors such as infrastructure, education, etc. On the topic of internet, several policies and frameworks have been developed by African governments in all regions of the continent. This includes: the ICT R&D Strategy19 developed in South Africa in 2007 and implemented under the Information

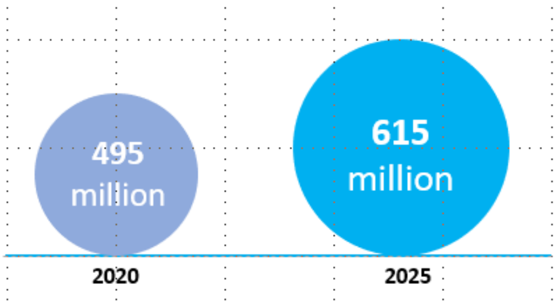
[18] https://au.int/sites/default/files/documents/38507-doc-dts-english.pdf
[19] http://www.ist-africa.org/home/files/RSA_ICTResearchDevelopmentInnovationStrategy_Final.pdf

Society and Development Plan, the National Policy for ICT20 in Senegal, the ICT Policy21 in Tanzania developed in 2003, and revised to ensure alignment with current countries priorities, the Kenya ICT policy22 developed in 2006, the National Policy for the Development of Information and Communication Technologies23 in Cameroon developed in 2007 and the Egypt National Strategy24 developed with a five-years timeframe.

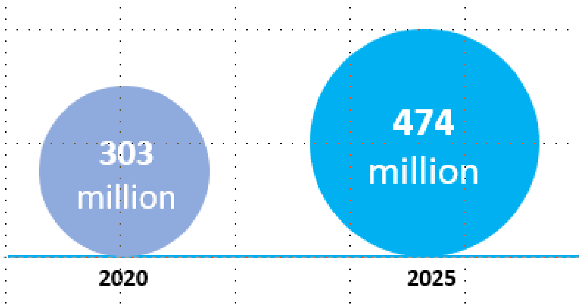
4.1.2. Evolution of the use of smartphones

The continent has been recording over the last years a continuous interest of its population in mobile devices and services. Indeed, it was recorded in 2020, that about 46% of the continent population representing 495 million people had subscribed to mobile services. A substantial increase of about 20 million from the previous year, for an estimated total number of subscribers by 2025 of 615 million representing 50% of the region's population. In addition, the use of internet services across the continent has also been gaining momentum over the last decades. From the 2001 – 2020 period, access to internet services have seen a tremendous increase on the continent. The total number of users of the internet grew from nearly 4.5 million people in 2001 to over 590 million by the end of 2020, representing an annual growth rate of 13% over the period (Internet World Stats 2021). A trend strengthened in the recent years by the COVID-19 pandemic and the need for adaptation measures to cope with the spread of the pandemic to ensure resilience and continuation of economic and social activities. From a recorded 303 million internet users in 2020, it is foreseen to have an additional 170 million people using the service by 2025, improving the internet penetration rate in Sub-Saharan Africa from 28% in 2020 to about 40% in 2025 (GSM Association 2021).

[20] http://www.ist-africa.org/home/files/Senegal_NationalPolicyonICT.pdf
[21] http://www.ist-africa.org/home/files/Tanzania_ICTPolicy.pdf
[22] http://www.ist-africa.org/home/files/Kenya_ICTPolicy_2006.pdf
[23] http://www.ist-africa.org/home/files/Cameroon_NationalICTPolicy_2008.pdf
[24] http://www.ist-africa.org/home/files/Egypt_ICT_Strategy_2007-11.pdf



(a)



(b)

Figure 15: Users in Africa: (a) Mobile and (b) Internet. Source: GSM Association (2021)

The penetration of digital devices and services is expected to contribute to the continent economy through the digital economy. Indeed, a study of the International Finance Institute reveals that the digital economy can contribute to 180 billion USD to the continent GDP by 2025 driven by an increased digital connectivity, and other factors linked to urbanization growth, access to cheaper equipment; and youth dividend and potential on the continent (Google & IFC 2020).

4.1.3. State of digital technologies specific strategies on the continent

Boakye (2021) clustered the different policies and frameworks into fundamental and emerging policies focusing on internet governance related to electrification efforts on the continent, and emerging topic in the global internet policy debate and captured in the AU's continental strategy respectively. The emerging policies topics designed and developed include Africa's Digital Single Market, Digital Rights, Digital taxes, Digital Economy – Start-ups and Innovation, and Cybersecurity.

With respect to specific technologies such as Artificial Intelligence and Blockchain, there is a limited development of different strategy documents framing the activities on the continent and in view of tacking advantage of the potential offered by these technologies. Unlike in developed countries where the development of the theses technologies is framed by robust strategic documents, in Africa only few countries are tacking actions in this regard. A recent study conducted by the OECD in 2019 reveals that the continent does not record countries with established and complete AI strategies. Only few countries such as Tunisia and Kenya are taking actions for the development of AI specific strategies (Berryhill, Heang, Clogher, & McBride, 2019). The constate is complemented by the Government AI Readiness developed by the Oxford Insights in 2021 which highlights that only one country on the continent Mauritius have develop a complete AI strategy (Oxford Insights 2021).

With regard to blockchain technology, unlike in other part of the world, the development on the continent is still very limited. Although there are few initiatives from actors from the private sector towards the development of blockchain-based solutions to existing challenges, at countries and continental level, there is still a lack of proper frameworks and strategies specific to the technology that can foster adoption and promotion in the continent. Indeed, as highlighted by an assessment conducted by OECD (2018), on blockchain projects worldwide with specific focus on the public sector, only few projects were identified on the continent in few countries: Mauritius and South Africa with a project each at exploratory, research or strategy level; and projects under the development or live in Ghana, Kenya and Senegal (Berryhill et al. 2018).

4.1.4 State of research on the topic of digitalization and mini-grid on the continent

Research in the topic gradually shifted from established institutions in developed countries and established economies such as China, the US and the UK in 2018 undertaking most of research work on the topic to new countries in Europe and Asia such as Finland, Portugal in Europe; and in emerging economies such as Saudi Arabia, Bangladesh and India in Asia; and Egypt and South Africa in Africa in 2021. In addition, while looking at the geographical distribution of the work done in the fields throughout the period 2018-2021, through the co-authorship analysis looking at the affiliation of the different authors with published articles on the topic of digital technologies in the wider energy sector, it appears that most of the research conducted on the topic are from authors affiliated in the institutions in Europe, Asia and America. The involvement of researchers from African institutions have so far been very limited on the topic. Few countries recorded research activities in the field and include institutions from countries such as Egypt, Tunisia and South Africa as shown on the figure 16 below.

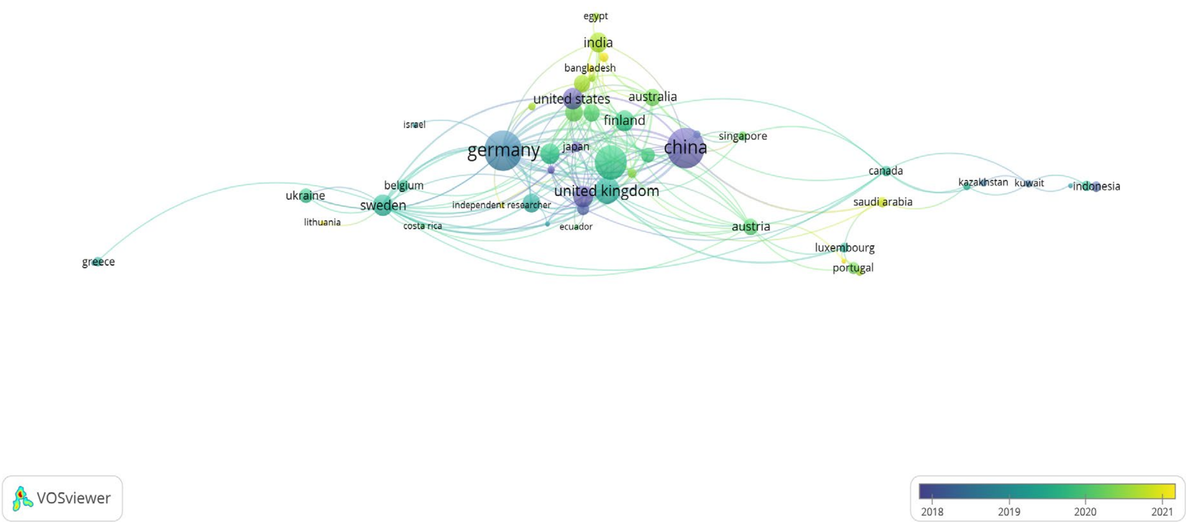


Figure 16: Co-authorship in research on the topic of digitalization and energy.

4.2. Challenges and opportunities for the mini-grid sector

4.2.1. Challenges

The mini-grid sector across the continent have recorded important advancement in the establishment of a suitable environment for the development and promotion of mini-grids with particular focus on rural electrification. This has resulted in fast tracking mini-grids penetration in several countries such as Tanzania, Kenya or Rwanda where a clear path for engagement in the mini-grid sub-sector has been prescribed including legal and regulatory framework, licensing requirements, and compensation mechanisms, etc. (USAID 2021). In contrast, although the digital technologies potential in boosting and improving the sector have been proven, the effective implementation of these technologies on the continent still faces some challenges for their full deployment in the sector for the benefit of the developer/operators and to a greater extend to the beneficiary populations including in remote localities of the continent.

4.2.1.1. Policy challenges

The existence of clear policy and regulatory framework is a fundamental driver of the development of a sector. The current status on the continent where very few countries have established policies and framework specific to mini-grid and further on digital technologies applications in the sector do not contribute to the wide promotion and deployment of the latter in the sector. indeed, the legal and regulatory framework is not evolving at the same pace of the digital technologies. in addition, and as general principle, sectors are governed by law and legal frameworks developed in the previous years25. Therefore, the absence of clear legal and regulatory frameworks for the deployment of digital technologies and associated/subsequent economies on the continent, especially in the energy and mini-grid sector are leading to inadequate protection of the different stakeholders and customers willing to invest engage in the different opportunities offered by the technologies.

4.2.1.2. Technical challenges

It is expected that the mini-grid sector will undergo thorough changes within the near future. Especially mini-grids powered by variable renewable energy technologies that require smart and digital technologies to balance electricity demand and supply and to ensure an efficient system operation.

The implementation of these technologies requires data to fueling the different processes. Indeed, digital technologies build their strengths on different parameters among which data which represent a critical one. The acquisition of such data in the African mini-grid context still represents a challenge especially given that data from operators and owners can be difficult to collect given that they constitute confidential information used for commercial purpose. With regard to the specific digital technologies such as artificial intelligence and

[25] Key issues for digital transformation in the G20
key-issues-for-digital-transformation-in-the-g20.pdf (oecd.org)

blockchain, the following challenges with respect to their application in the mini-grid sector were identified.

4.2.1.2.1 Artificial intelligence

The implementation and deployment of artificial intelligence in the mini-grid sector would have to overcome a set of challenges both from technical point of view and also from global respectively, national point of view. Indeed, the deployment of artificial intelligence in the sector is based on the intensive acquisition and use of data both in terms of quality and quantity, and the current status of the continent and particularly in the Sub-Saharan Africa with the lack of core infrastructures is a big challenge for the development and establishment of the AI ecosystems in the region. In addition, there is still a skills gaps in developing AI based-applications, and also implementing and accompanying the strategies concerning its wider application to the public sector. Indeed, the development of the technologies requires dedicated set of specific skills and capacities related to IT including coding, mastery of different learning that the continent is still yet to provide.

4.2.1.2.2 Blockchain

Among the challenges inherent to the implementation of blockchain technologies in the mini-grid space, we can cite the hardware requirements and regulation around blockchain. Indeed, an efficient deployment of blockchain within the mini-grid system, particularly through peer-2-peer energy trading needs a substantial penetration of appropriate metering infrastructures mainly smart meters to allow for the collection of relevant data for the process. In addition, the current nature of energy systems being regulated by governments in a centralized structure should be adapted/changed to allow/match the decentralized nature of the operations behind the implementation of blockchain-based technologies in the sector.

4.2.2. Opportunities for mini-grids

Given the wider consensus on the fact that mini-grids are among the viable solutions for off-grid electricity access in the continent, digital technologies deployment in the latter can contribute to the overall systems improved performance. It is acknowledged that most mini-grids on the continent26 have seen their reliability increased over the past years, to reach system uptimes close to 99% far better than what is offered by national electricity grids in bigger cities on the continent. Making electricity service quality even better than services offered in cities given the wide focus of the mini-grids on rural electrification and remote localities. While the reliability of the renewable energy systems is partly contributing towards this situation, it is to acknowledge that the implementation and adoption of digital technologies is also a major respectively critical factor.

Indeed, it is envisioned and expected that the mini-grid sector will undergo thorough changes within the near future. Indeed, most mini-grids are powered by variable renewable energy technologies, with solar PV-based mini-grids being the most common given its simplicity regarding the installation especially in rural and remote areas. A recent study of (SE4All 2020) suggests that solar PV represented up to 55% of the share of mini-grid installed globally more than ten-fold its share ten year earlier. This trend is even expected to continue as the technologies becomes more accessible on the market. In addition, the effectiveness of mini-grids in alleviating energy access poverty in rural Africa observed during the last decades and its high scaling-up potential on the continent reported by experts especially as contribution towards full access to electricity by 2030 (Lawrence 2020), will therefore require smart and digital technologies to balance electricity demand and supply, and to ensure an efficient operation of the systems.

Although mini-grid systems represent a cost-effective solution to addressing energy access challenges particularly in rural and off-grid areas in Africa, with over 7,181 mini-grids operating on the continent (SE4All 2020), they still encounter development and operationalization challenges related to the different functionalities of the systems. These

[26] This is reported from mini-grids of the African Mini-grids Association

challenges need to be addressed to achieve increased performance while reducing the operational costs and risks associated to their implementation.

Furthermore, digital innovations can address other challenges, e.g., optimizing project development processes, improving the design and planning of mini-grids as well as improving maintenance, management and customer related processes. With regard to the financial and sustainability challenge faced by most mini-grids in establishing stable markets around their system to ensure the full amount of the production will be consumed and paid by its customers, digital technologies can also play a role serving as enablers of new markets in the development and promotion of productive uses of electricity in the different beneficiary communities of the project. Indeed, recent research conducted by USAID reports that African off-grid electricity landscape often lack of productive uses of electricity by end-users which lead to an economic unviability of mini-grid due to limited demand (USAID 2021). The following highlights some specific opportunities for the digital technologies in the mini-grids on the continent:

1. Opportunity for payment energy services payment schemes similar to that of the mobile services in SSA building on the large share of people with limited or irregular incomes and the prepaid schemes that does not need any bureaucratic burden such as having a bank account, fixed monthly pay (Bazilian et al. 2013).
2. Investigating the potential to leapfrog market models in Africa using the sharing assets principle similar to what happened for the mobile phone sector.
3. Digitalization of the power sector (including mini-grids) assets is an opportunity for technological innovation. Indeed, the availability of the digital technologies across the world nowadays combined to the drastic drop observed on their costs during the last years offer a tremendous opportunity for innovation especially on the continent. Indeed, they can contribute through the data and analytics associated to improve the current structure of mini-grid systems and the power sector to a wider extend, from cost reduction of the existing and new projects across all types of power generation to the improvement of the technical performance of the systems and their competitiveness (IEA 2017).

4. Renewable energy potential harnessing: given the role mini-grid systems can play in rural as well as urban African areas in addressing the electricity access challenges of the populations, and the availability of a huge potential of renewable energy resources on the continent that can be harnessed in this regard, digital technologies with its potential to integrating large share of renewable energy sources is a great opportunity for the continent.
5. Opportunity for developing new market involving bidirectional transactions, and direct trading between prosumers and consumers within the microgrid environment using blockchain peer-2-peer energy trading.
6. Entrepreneurship and Youth opportunity for frugal innovation with the development of new and innovative solutions in the sector building on the availability and the low cost of the latter to develop. In fact, the deployment of digitalization and ICT in the mini-grid sector also comes with new entrepreneurship opportunities. With the development of technology, digitalization and the associated increasing ease of operation, various industrial sectors may identify mini-grids as a means to expand their business. Accordingly, new business models will evolve in the mini-grid sector. Furthermore, mini-grids can be instrumental for other sectors to explore and open up new markets in rural areas through cross-selling opportunities. Others may use mini-grids to get access to inputs/resources required for their businesses.
7. Further opportunities included the reduction of mini-grids O&M costs, improvement of the overall system efficiency, the reduction of the frequency of unplanned outages in the systems, the extension of operational lifetime of the systems with targeted and timely management of the systems.

4.3. Digital technology applications market potential in mini-grids in Africa

Notwithstanding the lack of clear strategies, policy and regulatory frameworks providing clear direction and tools for the establishment of digital technologies ecosystems in the mini-gris sector and in the wider energy sector, the private sector has taken steps and actions to take advantage of the opportunities offered by the digital technologies in the sector. Indeed, entrepreneurs from Africa and beyond have developed innovative solutions aiming at addressing the technological challenges in the mini-grid sector among which several are based on emerging digital technologies tapping on the enormous potential they offer. The African mini-grid market has seen in this respect the development and emergence of several technologies-based innovations and the prospect suggest a minimum market of existing mini-grid systems, which is planned to increase over the next decade to address electrification challenges across the continent. Indeed, estimates from the world Bank highlights that by 2030 about 210,000 mini-grids would be installed on the continent to provide electricity to over 490 million inhabitants provided that the investment and financing requirements and availability are met (Mwirigi 2022). Besides, the new consensus of the need to further develop incomes generating activities around mini-grid projects is an additional opportunity for the development of the digital technologies with the potential it offers. With regard to the huge potential and possibilities the technologies offered, several innovations have been developed on the continent with aim to take advantage of the technologies while addressing some the existing challenges faced in the sub-sector. While the gap to fulfill to take full advantage of these technologies is still yet to be filled, there are several innovators and entrepreneurs who have developed solutions building on these technologies in view of addressing challenges faced in the sector. A small snapshot of these innovations is highlighted in the table below:

Table 1: Selected use cases resp. innovations in the Digital Technologies and Mini-grid Nexus

Technology	Innovation	Mijni-grid functionality /value chain	company	Country
edge computing, cloud software and machine-to-machine communication	The energy autopilot for mini-grid demand side automation for real time grid operation automation	Demand-side Management	Steamaco[27]	Kenya
cloud accounting ledger	Automate and innovative payments solutions	Digital payment		
smart meters	Efficient data collection solutions	Demand-side management		
Smart meters	Plug-and-play metering solutions to electric grids including utilities and mini-grids sending regular reports on consumptions and power quality on a fifteen minutes basis	Demand side management	Sparkmeter[28]	Africa
Remote monitoring	real time monitoring service using cloud-based services	Operation and maintenance		
Smart meters	innovative solutions addressing the energy economics of complex energy systems using **smart meter** and internet-enabled	Generation and storage Demand-side management	Grit System[29]	Nigeria
Internet of Things (IoT)				

[27] https://steama.co/
[28] http://www.sparkmeter.io/
[29] https://grit.systems/

	technology to inform decision on the demand and production side of the system			
Smart meters	smart metering solutions that allow the monitoring of the generation and consumption while offering secured payment processing in the Nigerian market	Generation Demand-side Mgt Digital payment	ICE Commercial Power[30]	Nigeria
Internet of things	Provide supports companies in the energy sector in Uganda with advanced prototyping and energy system monitoring	Operation and Maintenance	Innovex[31]	Uganda
Smart meters	optimization of the cost related to the management of the electric distribution, while allowing end-users to monitor their own consumptions using a mobile application	Distribution and control Demand side management	Ndoto Sarl	Cameroon
Internet of Things	lower energy costs while increasing efficient use of energy	Operation and Maintenance		

[30] http://www.icecommpower.com/

[31] https://www.innovex.org/. In addition to the technical services offered by Innovex, specific training is offered to build the capacity of the youth with skills in electronics hardware and software applications.

AI-based remote monitoring	Web/platform that analyses and provides real-time monitoring of energy consumption to inform energy efficient decision making.	Demand-side Mgt	Wattnow[32]	
blockchain	Using the Ethereum crypto currency to develop an innovative and universal peer-to-peer solar cell leasing marketplace.	Digital payment	Sun Exchange[33]	South Africa
Artificial intelligence	Innovative **Artificial Intelligence** based systems to optimize energy generation	Generation and storage	RED+	Kenya
Blockchain	**blockchain**-based marketplace to facilitate the transactions between producers and consumers around the mini-grid systems	Digital payment		
Artificial intelligence	Development of a radically different approach to mini-grid architecture using artificial (swarm) intelligence which results in a substantial lower upfront investment per connected users in the mini-grid	Digital planning	FlexGrid[34]	Mali

32 https://www.wattnow.io/
33 https://thesunexchange.com/
34 https://www.flex-grid.com/

Cloud-based monitoring services & Pay-As-You-Go	Mobile payments without obligation	Digital payment		
PAYG	Innovative payment systems	Digital payment	RVE.SOL[35]	Kenya Mozambique
PAYG	Innovative payment systems	Digital payment	M-Kopa[36]	East Africa

35 https://www.rvesol.com/
36 http://www.m-kopa.com/

5. Conclusions

In Sub-Saharan Africa and around the world, mini-grids are a workable substitute to grid expansion as renewable energy generation technologies become more affordable and effective. While stand-alone solar household systems can serve areas with dispersed inhabitants, they can supply electricity to millions of people living in remote and rural towns with large populations. Digital technologies open up a wide range of possibilities for the mini-grid industry, including new funding sources, enhanced mini-grid functionality, and enhanced maintenance and customer management. Digital technologies could be utilized to improve productive purposes, whether through the use of digital appliances, access to information and learning platforms, or the development of new services linked to digital technology, with mini-grids assuring access to electricity.

On the other hand, using digital technologies in mini-grids in rural Sub-Saharan Africa presents new difficulties and dangers, particularly in terms of data security and privacy. The [37]following conditions must be met for Sub-Saharan Africa to fully utilize the potential of digital technology in order to create sustainable mini-grids throughout the continent:

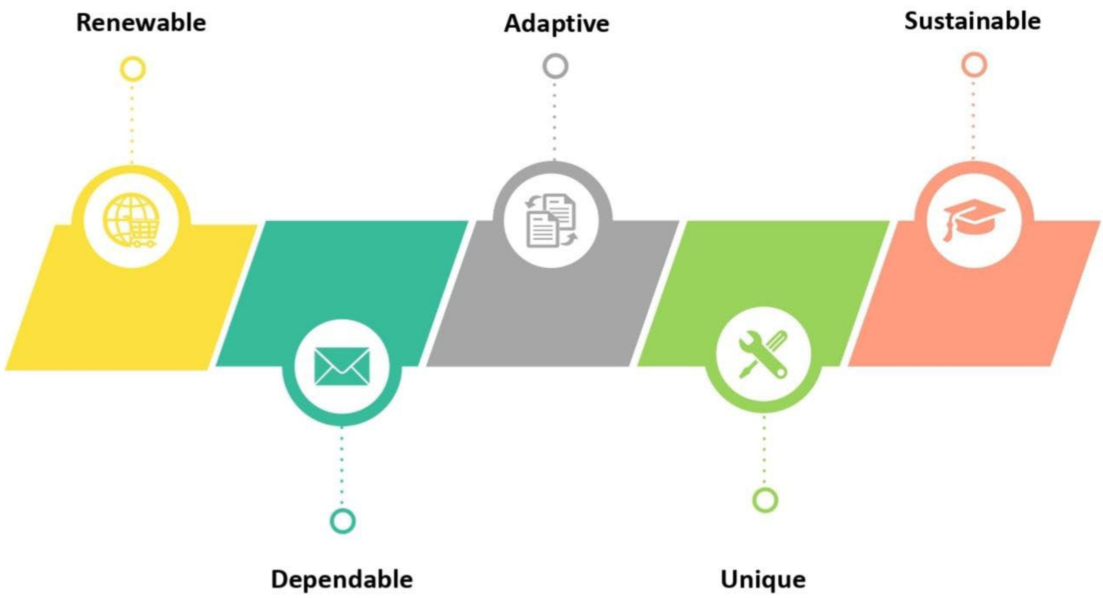


Figure 17: Requirements to harness digital technologies for mini-grids in Sub-Saharan Africa. Source: Own figure

[37]https://www.researchgate.net/publication/338646545_Exploring_the_nexus_of_mini-grids_and_digital_technologies

1) **Renewable energy should be used to power mini-grids**. Mini-grids are better able to handle the complexity issues that come with integrating intermittent renewable energy sources because to the use of digital technologies. For instance, proper management of electricity generation, storage, and demand can enhance the harmony and effectiveness of mini-grids powered by renewable energy sources. Digital technologies also make it possible to include more data, such weather forecasts, to create the best load plans for renewable mini-grids. Additionally, digital tools for planning and designing mini-grids could help identify locations that are best suited for using renewable energy sources.

2) **Electricity supply from mini-grids should be dependable**. Mini-grids' reliability is already increased by adequate demand estimation and sizing, which can be improved by digital technology. Remote control and maintenance will also lessen the amount of time the system is down. Power outages could be avoided with smart demand side management, which could reduce demand in situations where battery charging is low, for example.

3) **Mini-grids must be able to adapt to changing circumstances**. By enabling consumers to partially become electricity producers and possibly even exchange electricity with other producers on digital peer-to-peer trading platforms, digital technologies, in particular smart meters, could make it easier to set up more decentralized mini-grid configurations.

4) **Mini-grids should take into account the unique socioeconomic setting**. Digital planning and design technologies can be used in conjunction with traditional ways of design and planning to help incorporate pertinent data, such as the locations of homes, companies, community centers, and existing infrastructure. This would allow for a better accounting of the unique qualities of a certain location. If information on the evolution of community load profiles were to become available in the future, it could be used to enhance predictions of future power demand and help mini-grids be sized more appropriately. Tools for remote maintenance and support can also help to improve services for rural areas, cut down on downtime, and shorten repair periods. Last but not least, digital technologies already offer solutions for customer information and payment, for example through mobile payment apps, which may advance a design for these technologies that is acceptable and user-centered.

5) **Minimal environmental impact should be achieved using mini-grids**. Batteries are not only the most expensive and environmentally damaging component of the system, but smart management of mini-grids can extend the life of vital components like batteries. Predictive maintenance enables component failure to be foreseen even before it occurs, preventing further harm to the system and maybe lowering e-waste output. Digital technologies could be used to monitor mini-grid components at the same time to guarantee correct decommissioning, disposal, or recycling.

There are still many untapped opportunities that could arise from the integrated use of digital technology in and for mini-grids in Sub-Saharan Africa. Indeed, **digital technologies represent a great opportunity to address existing challenges in the mini-grid sector while leapfrogging the sector.** they offer a variety of possibility ranging from the possibility to harness further renewable energy sources and integrate them into the grid/system, to develop innovative payment and market models building on the experience in the mobile sectors and the possibilities offered by blockchain technology; the improvement of the technical performance and competitiveness of existing mini-grid systems building on the power of data and analytics while contributing to the increase of their operational lifetimes. Additionally, **digital technologies can leapfrog African youth entrepreneurship potential in the mini-grid sector.** Building on the potential of the African youth in innovation and creativity, digital technologies can contribute to further develop entrepreneurship opportunities in the sector. Building on the existing and identified use cases on the continent that cover almost all the functionalities and elements of the value chain of mini-grid systems, as well as the existing technologies, youth can have the opportunity while being inspired by the latter, to further develop solutions to identified challenges and thus create job opportunities in the sector. Furthermore, **there is an increasing interest in developing countries towards research on the topic of digital technologies and energy sector nexus.** There is a notable shift in research co-authorship during the past five years, with an increasing interest for research including in Africa with focus on countries such as Egypt and South Africa.

Besides, it appears that regulatory, economic, and socio-cultural framework conditions with a far greater influence are what are restricting the adoption of digital technologies in mini-grids rather than technological limitations, such as internet connectivity. Indeed, digital technologies have the potential to address many of the identified challenges faced in the mini-grid sector. their applications spectrum can range from a specific section of the mini-grid value chain or a single functionality of the system to a wider implementation of digital technologies into the design of the entire system creating full smart grid system. However, their implementation requires depending on specific applications some requirements both at technical and policy levels to be fulfilled and addressed for their successful implementation.

There is limited development of enabling environment regarding digital technologies on the continent. They are several challenges identified in the implementation of digital technologies in the mini-grid sector on the continent that hinder the adoption and limit the deployment of across the continent. The African landscape as far as digital technologies related strategy documents is concerned is still very empty. The development, adoption and deployment of digital technologies often require that at policy and decision-making levels, appropriate frameworks are established to allow and foster the emulation and development of activities in the sector by actors from the private sector. Unfortunately, although there are strategic documents existing at continental level, their translations into national contexts are still yet to be completed. Only few countries have moved toward the establishment of such framework with regard to specific technologies such as artificial intelligence and blockchain technologies.

The deployment of digital technologies in the African mini-grid space still faces several challenges at both technical and policy levels. The deployment of digital technologies in the mini-grid sector require to overcome some challenges identified both at technical levels. This includes the development and availability of infrastructures needed for the data acquisition given the important role and high dependency on data in the implementation of these technologies, the need for specific skills set and capacities related to Information Technologies to apply these technologies that are still yet to be fully available on the continent. Besides, technologies specific challenges such as policy and regulatory shifts and paradigms towards the integration of specificities of technologies such as blockchain and AI would need to be addressed.

To improve performance while lowering operational costs and dangers related to the deployment of mini-grids, these issues must be resolved. The incorporation of digital technology into mini-grids should be done to satisfy the needs of the customers of electrical services on the continent.

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