Working Paper

Energy Access for Sustainable Rural Development: Literature Review on Distributed Renewable Energy for Rural Electrification in Africa

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> *'Small-scale and decentralised renewable energy solutions can have significant benefits for human development and represent an important instrument for reaching the Sustainable Development Goals (SDGs) on the [African] continent.'*
>
> (Quitzow et al. 2016, p. 26)

Abstract

Access to electricity is a key mechanism for the improvement of living standards and community services such as healthcare and education, for the reduction of poverty and enhancement of gender equality. However, in 2016, 14 % of the world's population still lived without electricity, mostly located in rural areas of developing countries. Off-grid and mini-grid systems are summarised under the term 'distributed energy systems' and provide a fast and cost efficient method for rural electrification. Applicable technologies include solar photovoltaics, wind power, small hydro power and energy from biomass. Those small-scale renewable energy systems offer significant reductions in greenhouse gas emissions and other environmental impacts compared to fossil fuel energy generation. This paper reviews distributed renewable energy systems and concentrates on energy services for electricity generation in Africa. Whereas political uncertainty and a lack of finance are major barriers for implementation, the systems' contribution to energy security, their flexibility, modularity and environmental sustainability are driving forces for their expansion.

Keywords: *distributed renewable energy systems, off-grid, stand-alone, rural electrification, mini-grid, renewable energy, decentralised systems, distributed generation, electricity, small-scale generation, sustainable rural development*

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Introduction

Access to electricity is a prerequisite for human development. It contributes to a better quality of life and those who live in areas that are electrified gain improved health services and education, as well as economic opportunities. However, for most people in Africa, electricity is inaccessible, unaffordable and unreliable. Almost half of the continent's population lives without access to electricity, predominantly in rural areas in sub-Saharan countries (IEA 2017a, p. 80).

At the same time, inhabitants of rural areas also face water and food insecurity. There is a growing demand for energy, water and food, especially in developing countries, due to rapid economic growth, expanding populations and increasing prosperity. However, the ability to meet the growing demand for water, energy and food is restricted, as there are competing needs for limited resources. The challenge to meet the growing demand is further intensified by climate change (IRENA 2015).

Whereas past efforts mainly concentrated on centralised strategies (grid extension) in order to provide electricity, distributed electricity approaches increasingly gained momentum in recent years (Mandelli et al. 2016). However, the characteristics and benefits of distributed energy systems for electricity supply are often not known – a gap this literature review tries to fill.

This paper reviews distributed renewable energy systems and concentrates on energy services for electricity generation. Energy provision for heating, cooling and transportation are not part of this work. Although many of the findings of this review can be generalised and are applicable worldwide, the specific focus is set on rural areas in Africa.

Firstly, key issues of energy access in Africa are outlined, followed by an overview of ways to provide electricity in rural areas. Secondly, possible technologies and their environmental impacts are described. As financing can be a critical issue that is often discussed in scientific literature, ongoing investments, strategies, policies and private sector engagement for the financing of distributed energy systems are presented. Finally, opportunities and obstacles for distributed energy systems in Africa are discussed, where the many benefits will be further analysed.

Current Status in Africa

Despite great efforts in recent years, developing countries still lack access to electricity services. According to the International Energy Agency (IEA), approximately 1.1 billion people lived without electricity in 2016. This is a share of 14 % of the world's population, 84 % of which live in rural areas (IEA 2017a, p. 40). However, the extent of electricity supply varies greatly between different regions.

Africa is the continent with the lowest electrification rates. As presented in Figure 1, the development of electricity services in Africa differs widely. Whereas Northern Africa has nearly universal access to electricity, sub-Saharan Africa is the least electrified region of the world. Roughly 57 % of the population, around 590 million people, remain without access in that area (IEA 2017a, p. 80). South Africa is the outlier as it accounts for almost half of the power generation capacity on the sub-continent (IEA 2014; Quitzow et al. 2016).

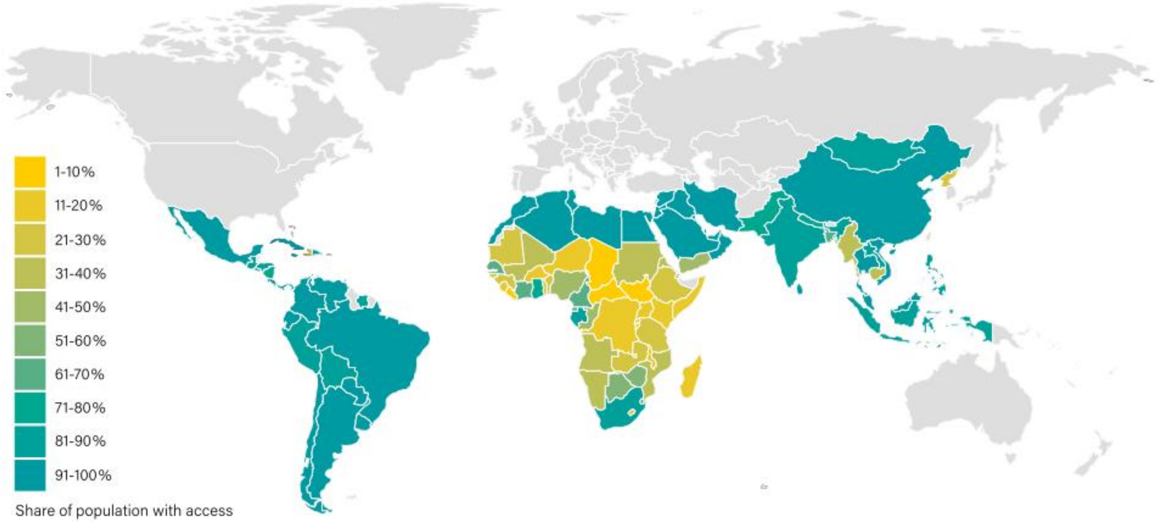

Figure 1 Electricity Access in Developing Countries, 2014 (REN21 2017, p. 98)

The electrification rates in sub-Saharan Africa show that access is particularly low in rural areas, with 80 % of those without access to electricity living in rural areas. The electrification rate of rural areas is lower than 25 %, compared to 71 % in urban areas (IEA 2017a, p. 80). This places a heavy burden on rural dwellers, as electricity access is a prerequisite for human development. It comprises education opportunities and health, but also affects agricultural or economic activities, as well as access to improved water resources and sanitation. At the same time, Africa will be one of the continents most affected by climate change and many countries will experience exacerbated water scarcity, health and food security risks (Quitzow et al. 2016).

Another significant obstacle that is often connected to missing electrification is the lack of clean cooking facilities[1]. Worldwide 2.7 billion people (38 % of the global population) are affected (REN21 2017, p. 98). In Africa, the vast majority of the affected population (792 million people) is primarily concentrated in sub-Saharan Africa (REN21 2017, p. 99). As a consequence, the main share of the population of sub-Saharan African countries lacks access not only to electricity, but also clean cooking facilities. Almost 80 % of the population of sub-Saharan Africa relies predominantly on solid biomass for cooking (IEA 2017a, p. 91). The dependency on biomass for cooking comes with severe health, social and environmental consequences. Each year, more than half a million premature deaths can be attributed to indoor air pollution caused by cooking in sub-Saharan Africa. On average, a household spends two hours for the collection and transport of firewood (IEA 2017a, p. 94). In some countries, for example Sierra Leone, this number goes up to five hours per day (IEA 2017a, p. 27). Mainly women and children are responsible for the provision and preparation of fuel, suffering most from detrimental health conditions and other drawbacks, as a huge amount of

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[1] According to IEA (2017a, p. 129), clean cooking facilities 'are considered safer, more efficient and more environmentally sustainable than the traditional facilities that make use of solid biomass (such as a three-stone fire). This refers primarily to improved solid biomass cooking stoves, biogas systems, liquefied petroleum gas stoves, ethanol and solar stoves'.

time could be used for other purposes (e.g. learning for school). In stressed areas, deforestation can be exacerbated because cooking with biomass results in a consumption of over 300 million tonnes of firewood per year (IEA 2017a, p. 94).

In conclusion the majority of the sub-Saharan African population lives in conditions of severe energy poverty, which is widespread in rural areas (Quitzow et al. 2016). There is a lack of adequate access to affordable, reliable, high quality, safe and environmentally sound energy services to meet basic needs. The following chapter will examine how rural areas can be electrified.

Pathways to Rural Electrification

In general, there are three main ways to provide electricity services: on-grid systems, mini-grid systems and off-grid systems. In the following these systems will be further described.

On-grid systems provide electricity through a connection to a local network that is linked to a transmission network (IEA 2017a). For most people around the world, electricity is provided by the electric grid, consisting of a large-scale integrated generation, transmission and distribution network (REN21 2014). Power is generated in large, centralised power plants using coal, natural gas, nuclear power, hydropower or solar energy as the energy source (IEA 2017a). However, decentralised generation can also be connected to the transmission network at low voltage (e.g. solar photovoltaic (PV) units). In order to supply rural areas, an existing grid is often extended beyond urban and peri-urban areas (REN21 2017). Especially in remote, scarcely populated areas in developing countries, grid connection is hindered by high investment costs for power distribution infrastructure in conjunction with low power demand (Sauer, Rau & Kaltschmitt 2007).

Mini-grids are localised power networks that do not transmit electricity beyond the area of service (IEA 2017a). They vary in size and are not connected to the transmission network, but have an independent distribution network (REN21 2014). They are commonly installed in remote areas to provide electricity to a relatively small number of concentrated located customers, usually a group of households and businesses (REN21 2017). In order to gain a stable flow of power that is required for all grid systems to work properly, mini-grids often use either a small diesel generator or battery systems for back-up (IEA 2017a). Mini-grids are based on modular generation technologies such as solar PV, wind turbines, small-scale hydropower and diesel generators (IEA 2017a). In some cases, connection of mini-grids to main networks is possible, if compatible. Usually mini-grids provide small-scale generation of 10 kW to 10 MW, whereas micro-grids offer a capacity range of 1-10 kW. However, there is no universal definition differentiating mini- and micro-grids (REN21 2017, p. 217).

Off-grid systems are characterised by not having connection to any grid (IEA 2017a). They are often called isolated (REN21 2014) or stand-alone systems (IEA 2017a; Sauer, Rau & Kaltschmitt 2007). They are used to power single households or businesses, where all generated energy is consumed on site (REN21 2014) or close by (REN21 2017). According to IEA (2017a), diesel generators and solar PV systems are dominant on this market.

Although all three described electricity systems may have distributed components, only mini-grid and off-grid solutions are usually categorised as distributed energy systems. This term is preferred by several authors, such as Ackermann, Andersson & Söder (2001) , Pepermans et al. (2005) or REN21 (2014), whereas other authors, such as IEA (2017b) use the term 'decentralised' systems.

According to REN21 (2017), distributed energy systems are characterised by either one of the following two conditions:

1. The production systems are rather relatively small and dispersed (e.g. small scale solar PV on rooftops) than relatively large and centralised,
2. Generation and distribution work independently from a centralised network.

Specifically, in the context of energy access both conditions need to be met in order to call a system distributed. This encompasses generation and distribution of energy services for power supply, cooking, heating and cooling independent of any centralised system in urban and rural areas in developing countries (REN21 2017). However, this is only one possible characterisation, as there is no consensus on a precise definition due to the many technologies and applications in different environments that are feasible (Pepermans et al. 2005).

Distributed energy systems already provide electricity to millions of people (REN21 2017). Especially in areas that have not yet been reached or are too expensive to electrify by grid connection, their numbers continue to increase annually. Small-scale off-grid electricity generation technologies can be used as a first step in the electrification process or as a building-block for future grid development (Mandelli et al. 2016). They can serve as a complement to or substitute of centralised energy generation systems (REN21 2017). Governments in sub-Saharan Africa rely on electrification through grid extension with an increasing share of renewable energy sources (IEA 2017a). The next chapter will present technologies for distributed electricity generation.

Renewable Electricity Generation Technologies for Distributed Energy Systems

Energy systems based on fossil fuels have adverse impacts on the environment. The combustion of fossil fuels (oil, gas, coal, peat) releases emissions into the environment that cause climatic changes, air pollution and adverse effects on human health. Worldwide, electricity and heat production was responsible for a share of 25 % of global greenhouse gas emissions in 2010. Therefore, electricity generation is a major driver of anthropogenic climate change and its resulting impacts on natural and human systems, such as increasingly frequent extreme weather events (Victor et al. 2014, p. 123). International environmental conventions target the reduction of greenhouse gas emissions, such as the United Nations Framework Convention on Climate Change (Bruckner et al. 2014). Moreover, combustion processes cause emissions of nitrogen and sulphur oxides as well as of other pollutants. The recovery and transport of fossil energy resources causes further pollution, effects on soils and ecosystems. In addition, the finiteness of fossil primary energy resources is also a driver for renewable energy sources (German Advisory Council on Global Change 2003).

Nuclear energy is challenged by socio-political acceptance, as it comes with severe safety concerns. Permanent disposal of nuclear waste is particularly challenging, as safe enclosure must be ensured over an extremely long period of time (Bruckner et al. 2014).

Consequently, this review focuses on renewable systems for rural electrification, which have significantly reduced adverse impacts on the environment compared to fossil fuel or nuclear energy generation.

Although the entire African continent makes up about 1 % of the world's CO_2 emissions (REN21 2017, p. 99), African countries can benefit from a low-carbon, climate-resilient development. The expansion of renewable energy offers an economically viable mitigation strategy (Quitzow et al. 2016). In addition, environmental co-benefits can be generated, namely improved air quality and mitigation of water-related risks (IRENA 2015; Quitzow et al. 2016). Also deforestation and environmental degradation can be reduced (German Advisory Council on Global Change 2009b; REN21 2017).

The following systems for electricity generation will be described: small-scale solar PV, wind turbines, small-hydro technologies and electricity from biomass. As the described technologies differ widely in their generation capacity, their specific application is diverse. Some systems may be used to provide lightning and mobile phone charging, others can be used to power machinery or community facilities, such as hospitals.

Photovoltaics

Electricity generation through PV directly uses solar radiation energy (Kaltschmitt & Rau 2007). The main component of such a system is the PV cell (also called solar cell) (EIA 2017a). It consists of semiconducting materials in which a light-induced charge separation (the separation of electrons from atoms) creates an electric current (REN21 2017).

The amount of electricity that can be produced is dependent on the number of PV cells or the surface area of a PV module. This makes PV power generation flexible. In addition, PV arrays can be installed quickly and are various in size (EIA 2017a). Due to this modularity of PV systems, there is a variation in application. The smallest systems are able to power calculators and wrist watches, while larger systems can provide electricity to pump water, power communication equipment and supply electricity for single homes, businesses or even small villages (EIA 2017a).

Pico-PV systems comprise the smallest distributed solar PV systems. These systems usually consist of a solar panel, a battery, one or more LED lamps and in many cases a mobile phone charging port (IEA 2017a). Generally, they have a power output of 1-10 W (REN21 2017, p. 219) and can substitute kerosene lamps, candles and battery-powered torches. They are by far the most widely used distributed renewable energy technology (REN21 2017). In 2016, more than 7.5 million pico-PV systems were sold worldwide. This represents 94 % of all off-grid solar product sales (REN21 2017, p. 100). However, it needs to be kept in mind that pico-PV systems offer very limited amounts of electricity.

Solar Home Systems (SHS) enable the provision of electricity for basic requirements regarding lighting and information of households (Sauer, Rau & Kaltschmitt 2007). This includes radio and television (REN21 2017), as well as information and communication technology (Alliance for Rural Electrification 2011) and refrigeration (REN21 2017). Figure 2 shows people using SHS for lighting and mobile phone charging.

Figure 2 People using light and charging a mobile phone through SHS

Additionally, non-domestic applications are possible, such as powering water pumping, cooling facilities, e.g. for medication, video sets for education and advanced training purposes (Sauer, Rau & Kaltschmitt 2007), telecommunications, navigational aids, health clinics, educational facilities and community centres (REN21 2017).

In 2016, more than 6 million SHS were in operation worldwide, benefiting 25 million people. Sales increased in 2016 compared to 2015, with a worldwide sale of about 377,000 (REN21 2017, p. 100). Predictions of the IEA (2017a) show that electrification through SHS will further increase in the future.

The previously presented solar PV systems mainly work with battery storage, however, there are also systems using other energy storage systems, for example PV pump systems. In such systems, pumped water is stored in an elevated tank in times with sufficient solar radiation available for operating the pump (see Figure 3).

Figure 3 A solar pump system is combined with drip irrigation at Faylar Village in Senegal

Initial costs for solar pumps are high, but such systems require little maintenance as they are a reliable and simple technology. In comparison to diesel pumps, no fuel needs to be purchased. That is why solar pumps offer a cost-effective alternative to grid- or diesel-based pumps, for example for irrigation (Omer & Omer 2007). Since operational costs of PV pumps are negligible, there are risks associated with excessive water withdrawal (IRENA 2015).

There are two main limitations of PV electricity generation based on the presence of sunlight. Firstly, the quantity of sunlight reaching the Earth's surface is not constant. The amount of sunlight varies depending on location, time of day, season and weather conditions. Secondly, the amount of sunlight reaching a certain area of the Earth's surface is relatively small. In order to gain a larger amount of energy, a larger surface area is required (EIA 2017e). Consequently, the largest amount of electricity is generated when PV cells and modules are directly facing the sun. Tracking systems can be used to move the modules constantly facing the sun. However, these systems are expensive. Instead, many PV systems have fixed modules with an angle of inclination that further optimises performance (EIA 2017a).

In recent years, off-grid solar energy (pico-solar and solar home systems of less than 100 W) has been one of the fastest growing industries in the provision of electricity access (Orlandi, Tyabji & Chase 2016; REN21 2017). In 2016, nearly 8.2 million off-grid solar systems were sold worldwide. That represents an increase of 41 % compared to 2015. In 2016, sales were the highest in sub-Saharan Africa, although they decreased in that region by about 1 million compared to 2015. India is the key market, followed by Kenya, Ethiopia, Uganda and Tanzania. In 2016, Eastern Africa accounted for an estimated 70 % of sales of pico-PV and SHS in sub-Saharan Africa. More than 30 % of people living off the grid in Kenya have a solar product at home. In Benin there was a fivefold growth of sales in 2016. This is caused mainly by active government engagement and to the introduction to Pay-As-You-Go (PAYG) models (REN21 2017, p. 99), that will be presented later in this work.

Wind Power

Wind power uses kinetic energy from moving air. The blades of wind turbines are caused to run because of the wind flowing over the blades, creating a lift. The blades are connected to a drive shaft that turns an electric generator that produces electricity (EIA 2017b). Small-scale wind turbines are in most cases coupled with a battery and a battery charge regulator (Kaltschmitt, Skiba & Wiese 2007) and provide electricity for farms, homes and small businesses, water pumping and telecommunication (Kaltschmitt, Skiba & Wiese 2007; REN21 2017).

Several definitions of small wind turbines exist. Technically, the standard IEC 61400-2 defines a rotor swept area of less than 200 m^2, equating to a rated power of approximately 50 kW generating at a voltage below 1,000 V AC or 1,500 V DC (WWEA 2017, p. 10). A rotor swept area of 200 m^2 equals a rotor diameter of about 16 m. However, the differentiation of small wind power is depending on the country (WWEA 2017). Several authors (Kaltschmitt, Skiba & Wiese 2007; WWEA 2017) use an upper nominal capacity limit of 100 kW in their definitions. This limit is mainly based by the leading role of the North American and European markets (WWEA 2017, p. 10). The Alliance for Rural Electrification (2011, p. 18) states that most small-scale wind turbines in rural areas have a diameter of up to 7 m and a power output between 1kW and 10 kW. In case of rural household supply, even wind turbines below a diameter of 2 m and with a 1kW output can be used (Alliance for Rural Electrification 2011, p. 18).

In order to properly operate a small wind turbine, careful planning is required. Wind is always in a non-steady state due to the wide temporal and spatial variations of wind velocity (Omer & Omer 2007). Accordingly, an adequate location of the wind turbine is a key requirement for successful small-scale wind power projects and should be carefully studied. Wind measures might be necessary prior to installation. However, in relation to the output and added value of the wind turbine, long-term wind studies are often too time consuming or costly and therefore often avoided by project developers (Alliance for Rural Electrification 2011). In addition, wind data is very sparsely collected in Africa, which makes not only the development of wind energy difficult, but also hinders the reduction of detrimental effects of wind and related drifting sand in building activities, agriculture and wind-related disasters, such as erosion or fire (Wisse & Stigter 2007). Generally speaking, wind speed increases with altitude and over open areas without windbreaks. The tops of smooth, rounded hills, open plains and water and mountain gaps that funnel wind are therefore good sites for installation (EIA 2017c).

Small-scale wind systems are spread around the world. China, reaching 415 MW in 2015, accounts for 44 % of the global installed capacity. Other developing countries only offer limited amounts of small-scale wind power capacity. Among African countries, solely Morocco is listed in the top 24 producing countries, with a total capacity of 700 kW as of 2012 (WWEA 2017, p. 5).

Hydropower

Hydropower harnesses the potential energy within falling water (Jorde & Kaltschmitt 2007a) or the kinetic energy in streams. In case of hydroelectric power generation, this energy is converted into electricity (Jorde & Kaltschmitt 2007a). However, often the term hydropower and hydroelectric power are used interchangeably.

In regard to hydropower, a distinction is drawn between small-scale and conventional, large hydropower plants. However, these are not competing components of the hydropower sector, as small-scale hydropower plants are, among other aspects, mainly located in smaller rivers (Couto & Olden 2018). In contrast to conventional hydroelectric power plants, they exhibit little to no water storage capacity, making locations with steady flow the most suitable for those systems. Furthermore, areas with an elevation drop, high annual precipitation rates and catchment areas with a supply of water into the rivers offer best resources (Alliance for Rural Electrification 2011).

The classification small-scale hydroelectric power is used frequently, but is often not further defined. Similar to the discourse on defining small-scale wind power systems (see p. 10), definitions are often based on generation capacity and vary substantially. The generation capacities of small-scale hydroelectric power plants are classified as:

- up to 50 MW in Canada, China and Pakistan (Couto & Olden 2018, p. 93),
- up to 10 MW in Russia (Jorde & Kaltschmitt 2007b, p. 354),
- up to 1 MW in Burundi (Couto & Olden 2018, p. 93) and Germany (Jorde & Kaltschmitt 2007b, p. 354) and
- up to 300 kW in Switzerland (Jorde & Kaltschmitt 2007b, p. 354).

About 70 % of the countries define installations with less than 10 MW as small-scale plants (Couto & Olden 2018, p. 93; UNIDO & ICSHP 2016, p. 11), a value that is increasingly accepted as the international standard (Couto & Olden 2018, p. 93). Looking more closely at publications with a focus on rural electrification other definitions occur. Small-scale hydroelectric power systems are defined generally with less than 100 kW (REN21 2017, p. 101). As suggested by the Alliance for Rural Electrification (2011, p. 22), systems can be divided into:

- small hydropower plants (less than 10 MW),
- mini hydropower plants (less than 1 MW),
- micro hydropower plants (less than 100 kW) and
- pico hydropower plants (less than 20 kW).

In addition to this significant variation in definitions and wide range of scales of capacity across countries, the design of small-scale hydropower plants is also diverse. There might be significant differences in dam sizes, reservoirs, storage capacity, outlet structure or plant operation (Couto & Olden 2018). The technology of a hydropower system can be categorised into run-of-river, reservoir-based capacity and low-head in-stream technology (REN21 2017). Turbines are the most expensive part of a small hydroelectric power station. The Alliance for Rural Electrification (2011, p. 23) gives an overview on the most important types of hydro turbines and generator types. For a more detailed description about turbine layouts and function of different turbine types, including their efficiency curves see Jorde & Kaltschmitt

(2007b, p. 363) or Williams & Simpson (2009). Small hydropower systems can be used for distributed power generation, but also for forms of mechanical power, such as irrigation or pumping (REN21 2017).

Beside the choice of the system, the plant's layout and surroundings are a major concern in planning, as hydropower particularly has a higher interaction with its environment than other power systems. Sound knowledge of the site's geomorphology and hydrology are necessary in order to predict the availability and time distribution of flow rates. This expertise should include the maximum flood of the river to avoid any damages. Proven specialists are recommended for flow rate evaluation and environmental engineering should be involved for the assessment of landslides, instability and other factors, such as fish migration (Alliance for Rural Electrification 2011).

Hydroelectric power is significantly the world's primary source of renewable electricity, with a share of 16.6 % of global electricity production in 2016 (REN21 2017, p. 33). Although 91 % of all hydroelectric power plants are considered as small-scale plants, they contribute to just 11 % of the global electricity generation capacity of hydroelectric power (Couto & Olden 2018, p. 93). The latest World Small Hydropower Development Report gathers information on the status quo, future potential, policies and barriers for small hydro development for each country (see UNIDO & ICSHP 2016). According to this report, in 2016 the globally installed small-scale hydropower (smaller than 10 MW) capacity was about 78 GW (UNIDO & ICSHP 2016, p. 7). The African continent has an installed small-scale hydroelectric power capacity of 580 MW and considerable potential for development (UNIDO & ICSHP 2016, p. 12).

Energy from Biomass

In general, biomass is defined as organic material. That means it comprises material that contains carbon, such as plants and animals and resulting residues, by-products and waste (e.g. animal excreta) and dead, but not yet fossil organic materials (e.g. straw) (Kaltschmitt 2007).

Available biomass can be processed and converted into useful energy by means of a great variety of technologies. A range of wastes, residues and crops grown for energy purposes can be used (REN21 2017). The easiest implementation is to burn woody biomass directly after mechanical preparation, but for other promising applications a conversion of biomass into a liquid or gaseous secondary energy carrier is required. The available processes for the conversion are generally divided into thermo-chemical, physical-chemical and bio-chemical processes (Kaltschmitt 2007).

Although it is technically possible to use bioenergy-based technologies in rural areas (German Advisory Council on Global Change 2009b), Mandelli et al. (2016) do not suggest their usage, mainly due to the fact that the minimum plant size for electricity production does not fit stand-alone, but rather micro-grid scale and that significant concerns regarding sustainability arise if used in rural areas. Other authors, such as the Alliance for Rural Electrification (2011), IEA (2017a) or REN21 (2017), also do not list bioenergy technologies for electricity supply in rural areas. Nevertheless, energy from biomass is primarily used for cooking and heating purposes in rural areas.

Renewable Hybrid Systems

In hybrid systems, different power generators complement each other in terms of time availability. This ensures a steady energy supply, as the energy quantities of the previously characterised power systems are influenced by fluctuations due to varying weather, availability of sunlight or changing seasons. For example, PV systems can only supply as much electricity, as is obtained from the solar radiation. During cloudy days or nights, less or no electricity is produced. Therefore, hybrid systems are used if a reliable energy supply that is independent of weather conditions or season is required (Sauer, Rau & Kaltschmitt 2007).

Different configurations of hybrid systems exist. The simplest technology is to couple a renewable energy technology, e.g. solar PV, with a traditional, resulting in a PV-diesel system. More complex is the combination with a storage technology, e.g. a wind-diesel-battery system (Mandelli et al. 2016). Renewable energy hybrid systems combine two or more renewable power technologies (REN21 2017). Particularly if the site offers both, sufficient solar radiation and above-average wind conditions, wind-battery systems may be combined with PV modules to wind-battery-PV systems (Kaltschmitt, Skiba & Wiese 2007). Wind energy converters and solar energy systems complement each other well on many locations with regard to seasonal and weather-related fluctuations (Sauer, Rau & Kaltschmitt 2007).

Mini-grids (or micro-grids) can be installed as a single distributed energy source or for hybrid technologies. Globally the deployment on mini-grids increased and there is a growing interest in their interconnection with centralised grids and/or other mini-grids. In 2016, more than 23 MW of mini/micro-grid projects based on solar PV and wind power were announced, mostly in Africa. For example, Madagascar partnered with Fluidic Energy in order to provide electricity to 100 remote villages, including 400,000 people through a 7.5 MW solar PV mini-grid (REN21 2014, p. 101).

Energy Storage Systems

As mentioned before, some renewable electricity generation technologies face the challenge of variability in production. If the generated electricity is not directly consumed, it needs to be converted immediately. Storage systems are required to balance the difference between supply and demand. Several storage technologies exist (Díaz-González et al. 2012). Most commonly, battery systems are used for small to medium scale applications (Beaudin et al. 2010). However, especially in mini-grid applications, storage can be technically challenging.

As shown in this chapter, there is comprehensive technological expertise for rural electrification. As the quantity of installations of distributed renewable electricity systems is growing, adverse environmental effects should be avoided.

Environmental Impacts

Even small-scale electricity systems cause impacts on the environment. In principle, these might not be that different from those of large centralised renewable power plants, but their size makes the difference. In the following, the main concerns will be briefly described and a concept will be presented that allows a holistic view on the interconnections of water, energy and food supply.

Key Impacts of Distributed Renewable Energy Technologies

Regarding PV systems, environmental impacts are primarily related to the manufacturing of solar cells. The main areas of concern are the consumption of scarce mineral resources and the toxicity of used chemicals. The specific effects are largely dependent on the type of solar cells used for the PV system (mono-crystalline cells, multi-crystalline cells, ...) (Kaltschmitt, Schröder & Schneider 2007). A more detailed analysis of these severe effects is provided by Kaltschmitt, Schröder & Schneider (2007, p. 292). Recycling of solar cells is still at its infancy and sophisticated chemical separation processes are required. Tao & Yu (2015) emphasise the importance of an efficient collection network for expired PV systems. It is questionable if PV recycling infrastructure planning reaches remote areas. In addition to these effects, it needs to be kept in mind that ground-mounted PV systems partly or entirely inhibit the use of ground (Kaltschmitt, Schröder & Schneider 2007).

Looking at wind turbines, the use of rare earth minerals and the mining of those minerals may have severe environmental effects (EIA 2017d). Sound emissions might occur during operation, due to the aerodynamic noise at the rotor blades (optimisation is possible by adjusting the shape of the rotor blade and the blade tip). There is the danger of interference with feeding and resting birds, impacts on flying or migrating birds and even hitting of birds (Kaltschmitt, Skiba & Wiese 2007). In addition, the EIA (2017d) reports the death of bats.

Inappropriate planning and design of hydropower plants can have negative effects on the environment (UNIDO & ICSHP 2016). Couto & Olden (2018) even state that there is scientific evidence that indicates substantial environmental impacts of small hydropower plants . As discussed earlier in this paper (see p. 11), there is a significant variation in country-specific classifications of small hydropower plants based on their generation capacity. Consequently, there are varying small power plant layouts that are strongly correlated with their environmental impacts. In addition to that, the diversity of operation modes and sizes of small hydropower plants produce a variety of ecological consequences. These may not necessarily vary from those expected for large hydropower plants. The magnitude of impacts depends on the attributes of specific projects and their landscape context. However, these impacts are underestimated by existing policies and regulations, as environmental regulations are based on the capacity definition of small hydropower plants that is not necessarily fitting to the magnitude of their environmental impacts caused by the diversity of sizes and operation modes. The emphasis of ‘small’ in small hydro policies is equated with negligible environmental impacts (Couto & Olden 2018). Most importantly, there are three areas that cause environmental effects during small hydropower operation: impoundments, barrier effects and diversion effects. These may result in a loss in biodiversity, interrupted migration of fish, change in the composition of species (including mammals, birds and amphibians because of the changed food availability), effects on ecosystems in the lower course of a river, limited reproduction of certain types of fish, isolation of various fish populations or the reduction of flow in the river. Kaltschmitt & Jorde (2007, p. 379) give a more detailed overview of the specific consequences. Above all, these effects are amplified when several power stations are linked up in a series (Couto & Olden 2018; Kaltschmitt & Jorde 2007).

The main discussion in the field of bioenergy concentrates on the competition in the cultivation of food and energy crops for the available land, but also for the available water. This discussion is rather complex and cannot be fully portrayed here, however, a detailed analysis of the topic is given by the German National Academy of Sciences Leopoldina (2012) and German Advisory Council on Global Change (2009b). Energy crop cultivation may displace existing food production, with the consequence that food production must be transferred to other unspoiled areas. As an indirect consequence, forests may be cleared, sometimes even in other countries and the loss of biological diversity may be further exacerbated. In addition, there is already an increasing demand for land worldwide and predictions of the Food and Agriculture Organization of the United Nations foresee a rising demand for land for food production for the increasing world population. Conflicts over land can be one consequence (German Advisory Council on Global Change 2009a). Mandelli et al. (2016) see a sustainable use of bioenergy for power generation as quite difficult in rural areas, because of the complexity of the supply chain and thus the required local capacity and very specific and comprehensive analysis at the local level. Additionally, they claim that many countries lack institutional structures in order to support the development of new bioenergy technologies (i.e. new resources).

Distributed renewable energy technologies are commonly coupled with battery storage systems. Batteries can be inefficient and are made of resources with high environmental and energy impact. Toxic components, as well as scarce resources, namely lithium, are used for manufacturing. Thus environmental impacts of mining need to be considered (McManus 2012). Although recycling is technically available it is again questionable if batteries used in remote areas ever reach recycling stations. Institutional agreements need to be in place to for the recycling of expired batteries (Berger 2017).

To sum up, it can be said that especially stand-alone energy systems offer a reasonably good level of sustainability. Stevens & Gallagher (2015) further add that those systems may perform below their optimum and fail to fulfil the full needs of the community without sufficient focus on the water, energy and food nexus.

Distributed Renewable Energy Systems in the Water, Energy and Food Nexus

The water, energy, food nexus is a concept that is increasingly recognised. It emphasises the interconnections and interdependencies between water, energy and food supply (Hoff 2011; Stevens & Gallagher 2015). Water and energy footprints of food production are significant on local, national and global scales. Energy is used in agricultural production for water pumping, irrigation, mechanised agriculture, processing of harvest, transportation (IRENA 2015) and mineral fertiliser production (Bernstein Lenny et al. 2007). At the same time, poor agricultural practices lead to soil erosion, deforestation and negatively affect the availability and quality of water resources. There is a competition for land and water resources between energy and food production activities that might lead to food-fuel tradeoffs. Particularly for remote communities in developing countries, distributed energy systems play an important role in water treatment and in addressing clean water availability problems (Guta et al. 2017; IRENA 2015).

Hoff (2011) outlines a considerable overlap between the people without appropriate access to water, the ones who are undernourished and those without access to electricity. The nexus approach offers perspectives on the implementation of integrated solutions for the management of environmental impacts and allows a holistic understanding of unintended consequences of policies, technologies and practices. It represents a multi-dimensional means for the description of the complexity and nonlinearity of interactions of humans and environment (Kurian 2017). Consequently, the nexus affects the extent of the simultaneous achievement of water, energy and food security objectives, making it a major consideration in the sustainable development strategies of countries and forcing governments, the private sector, communities, the academic world and other stakeholders to investigate integrated solutions to ease the pressure and to formulate development strategies based on a sustainable and efficient use of scarce resources (IRENA 2015).

Renewable energy technologies can address some of the trade-offs between water, energy and food and bring significant benefits in all three sectors. Compared to conventional energy technologies, renewable energy technologies can reduce the competition by providing less resource-intensive processes and technologies. Especially distributed renewable energy technologies can offer integrated solutions for expanding access to sustainable energy while at the same time ensuring security of supply across the three sectors (IRENA 2015). According to Stevens & Gallagher (2015), improved energy access, low external input and agro-ecological approaches offer the best opportunities for sustainability. Successful connection with local market systems for the produced crops and products is required to maximise the benefits regarding poverty reduction.

Realisation of Distributed Renewable Energy Systems

This chapter tackles the question of how to realise distributed renewable energy systems in rural areas. It covers investment and financing of those systems, including private sector engagement, such as the PAYG business model. In addition, ongoing donor initiatives and programme developments are discussed. Lastly, strategies and policies of several African countries are presented.

Investments

Globally, the main source of finance for investment in energy access is funding from multilateral organisations and bilateral donors. However, looking more closely at the total energy investment of major multilateral donors shows that the share of investment provided for energy access and distributed renewable energy is comparatively small. In 2015, the total energy investment comprised USD 17,436 Million. From this, USD 2,798 Million were invested in energy access, but only USD 286 Million in distributed renewable energy (REN21 2017, p. 105).

While public international finance for climate change and clean energy systems covered in total about USD 14.1 billion from 2003 until 2015, only 3 % were allocated to distributed renewable energy systems. That is why debt financing, equity and to some extent grants are the main source to finance the distributed renewable energy sector (REN21 2017). For example, through the Sustainable Energy Fund for Africa (SEFA), the African Development Bank (AfDB) awarded USD 1 million to the Republic of Niger and USD 840,000 to Rwanda to foster the development of mini-grids (REN21 2017, p. 105).

Private Sector Engagement and Business Models

In order to meet Africa's investment needs in the energy sector, significant private sector engagement is crucial. Substantial efforts have been made in a number of countries to improve the role of independent power producers. Currently, the market for SHS and other off-grid renewable energy services is experiencing a rapid expansion lead by the private sector. What is more, there is an increasing trend of international private equity targeting the renewable energy sector in Africa, mainly regarding wind and solar (Quitzow et al. 2016).

An emerging innovation in off-grid technologies creates economic and entrepreneurship opportunities for African companies (Quitzow et al. 2016). There are some new financing business models for distributed renewable energy systems that have shown notable success in several African countries (Quitzow et al. 2016). In 2016, the most popular models were the PAYG model for stand-alone systems, distributed energy service companies (DESCOs) for mini/micro/pico-grids and microfinance and microcredits.

These business models have been revolutionised by technological advances. For example, it is becoming increasingly common to pay for energy services via smartphone (REN21 2017). In some sub-Saharan African countries, more households own mobile phones (more than a quarter are smartphones), than have access to electricity. This helps to increase access to a large array of energy services in rural areas. Especially in East Africa, digital mobile-enabled platforms and mobile money are used for the distribution of decentralised energy systems. More and more companies target areas without electric connection, but with mobile phone reception (IEA 2017a).

The PAYG model will be further described in the following. In addition to regular fixed payments through mobile money services via phone, customers pay an upfront fee in exchange for an energy product. This model is a rapidly growing energy access solution (REN21 2017). The market leader, M-KOPA SOLAR, has connected about 600,000 households to solar power systems in Eastern Africa. Some 500 new SHS were installed every day (M-KOPA SOLAR 2018; REN21 2017). However, criticism about their business model exists. Notably, in an article published in Bloomberg Businessweek, Faris (2015) accuses M-KOPA SOLAR of making profit off of poor Africans. Initially M-KOPA SOLAR sells SHS, but tries to sell more products on instalment to the customer. Therefore M-KOPA SOLAR is rather a finance company trying to build a long-term finance relationship by offering more products. To customers it might not be clear that they enter a financial – and not a traditional retail relationship. The revenue of the company located in Nairobi was USD 30 million in 2015 ,with an estimated doubling in 2016 and further growth plans (Faris 2015). In addition, the company can remotely monitor products and collect usage data. They can also disable a device in case a customer misses a payment and switch the device back on, when the payment has been made (IEA 2017a).

PAYG schemes offer the potential to enhance the scaling-up of off-grid renewable energy services for customers with low and irregular incomes. At the same time, the local off-grid industry can be expanded (Quitzow et al. 2016). These energy services are mostly active in Kenya, Tanzania, Rwanda and Uganda, but other markets, especially in Ethiopia, Ghana and Nigeria are opening. Some governments are entering partnerships with companies to tackle the distribution of renewable off-grid systems. Recently the Republic of Togo partnered with the company BBOXX for the distribution of more than 300,000 SHS in Togo in the next 5 years (IEA 2017a).

For PAYG energy services mainly solar systems are used. The most popular is the installation of SHS that consist of a solar module, a battery and small appliances, such as LED bulbs or mobile phone chargers. On average, customers gain low levels of power, but if highly energy-efficient appliances are used, the effectiveness can be enhanced and more energy services at lower cost are offered (IEA 2017a). On a smaller scale, this business model is used to supply productive uses (e.g. water pumping or agro-processing) and clean cooking (REN21 2017).

Investments in off-grid solar PV systems are dominated by investments in PAYG companies. For example, during 2016 the Nigerian off-grid solar company Lumus Global raised USD 90 million of funding through debt financing and equity to further develop its operations. This is one of the largest amounts raised by a single company in one year in the entire sector (REN21 2017, p. 106).

Other, alternative funding mechanisms such as crowdfunding continued to promote the development of small decentralised renewable energy system companies and initiatives. In 2015, USD 3.4 million were raised. Crowdfunding for clean cooking stoves in the private sector is also gaining popularity (REN21 2017, p. 106).

Donor Initiatives and Programme Developments

All major bilateral and multilateral donor agencies actively support renewable energy projects in Africa and have launched a significant number of new initiatives to support the renewable energy sector in Africa. One example of the role of renewable energy in international development cooperation is the UN Sustainable Energy for All (SEforALL) initiative launched in 2011 (Quitzow et al. 2016). The initiative has three main objectives:

1. to ensure universal access to modern energy services,
2. to double the global rate of improvement in energy efficiency and
3. to double the share of renewable energy in the global energy mix.

Key to this initiative is the development of Country Action Agendas that outline short- to medium-term projects and programmes (Quitzow et al. 2016; SEforALL 2018). The SEforALL platform brings various actors together in order to create effective coalitions and partnerships. It focuses on capacity building in governments, organisations and private sector actors (REN21 2017). In addition to SEforALL, major political initiatives exist on the regional and sub-regional level. These support political dialogue between African countries and donor agencies (Quitzow et al. 2016). According to REN21 (2017), the most far-reaching and influential programme are the SDGs set by the United Nations. For more programme developments with regard to distributed renewable energy see REN21 (2017, p. 109).

Strategies and Policies

In order to support the deployment of renewable distributed energy services, many countries use policy measures. These cover dedicated electrification targets, specific targets for distributed renewable energy technologies, fiscal incentives, regulations, auctions, exemptions on value added tax (VAT) and import duties (Brent 2016; REN21 2017).

Several countries also developed dedicated institutions to support renewable energy development, such as the Centre for Renewable Energy and Energy Efficiency in Cap Verde that promotes renewables (Quitzow et al. 2016). In 2016, the Nigerian Electricity Regulatory Commission announced plans to finalise its mini-grid regulation, in order to streamline permit and tariff procedures (REN21 2017).

Strategy plans are implemented in order to move away from the strategy of grid expansion for rural electrification. More recently, policies were implemented by several countries for decentralised approach of rural electrification based on renewable energy sources. For instance, Uganda adopted the Rural Electrification Strategy and Plan of 2013-2022 that includes support for community-based[2] mini-grids and solar PV systems (Quitzow et al. 2016). Rwanda released targets to increase access to electricity to more than 70 % by 2018, of which 22 % will be through off-grid connections. Kenya implemented a Feed-in-Tariff in 2012 that includes solar mini-grid systems (Quitzow et al. 2016). Sierra Leone exempted all VAT and import duties from SHS (REN21 2017).

In addition, quality assurance frameworks were set into place for off-grid solar product in order to reduce the sale of low-quality offerings on the market (REN21 2017). In 2016, the Economic Community of West African States (ECOWAS) approved a quality assurance framework for off-grid rechargeable lighting appliances, which may be included into national legislation of member countries (REN21 2017).

Opportunities and Obstacles of Distributed Renewable Energy for Rural Electrification

In the course of this literature review, some features of distributed renewable energy systems were already discussed. The following chapter concentrates on the chances and possibilities for, as well as constraints to the implementation of those systems and their role in rural electrification.

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[2] Community energy is described by REN21 (2017, p. 214) as ‘an approach to renewable energy development that involves a community initiating, developing, operating, owning, investing and/or benefiting from a project. Communities vary in size and shape (e.g., schools, neighbourhoods, partnering city governments, etc.); similarly, projects vary in technology, size, structure, governance, funding and motivation.’

Energy Access

First and foremost, distributed energy systems significantly contribute to energy access. Distributed renewable electricity systems provide affordable lighting and enhance communication (REN21 2017; Trotter, McManus & Maconachie 2017), which has also a great impact on improving the quality of education.

Globally, there are approximately 200 million children that attend primary and secondary schools that have no access to energy services. Quality education is a key driver for sustainable development. Access to electricity offers, for example, prolonged time for reading and homework (lighting), access to information and knowledge (computer) and expanded vocational offerings in engineering, welding, metalwork, carpentry (school laboratories and workshops). The imbalance between rural and urban communities can be shifted by making rural dwellers more competitive (Hirmer & Guthrie 2017). Teachers can also be attracted to rural areas (Mandelli et al. 2016).

The ability to use the internet allows access to open source knowledge. For instance, Open Source Ecology (2018) offers construction manuals for several machines. An example is Libre Solar, an open hardware project currently with focus on solar electricity generation and storage (Libre Solar 2018). An online step by step tutorial created by Collective Open Source Hardware (2018) shows how a modular system can be set up, depending on power and storage capacity requirements. Electrical circuit boards are interconnected between energy producers (e.g. as solar panels), energy storage (e.g. lithium-ion batteries) and the load (appliances such as a computer). The tutorial can be found at the Collective Open Source Hardware (2018) website.

Access to electricity improves quality and availability of health services and well-being. A reliable electricity service in health clinics and hospitals can significantly enhance a multitude of health services, such as vaccinations (refrigerator/freezer), emergency response (mobile phone), improved medical equipment, public health education (television, smart phones), night-time care and child delivery at night (lighting) (Hirmer & Guthrie 2017). Adair-Rohani et al. (2013, p. 254) show that although 96 % of hospitals in Kenya have power supply, only 24 % have reliable electricity. In Kenya, 72 % of other health facilities are connected to electricity, but only show 15 % reliability. These numbers emphasise that health care workers are often forced to work with torches or polluting and dangerous kerosene lamps (Adair-Rohani et al. 2013). Another example among many is the installation of street lightning, which increases the safety of communities, as injuries, animal attacks (e.g. snakes) or attacks of thieves can be prevented (Hirmer & Guthrie 2017).

There are also positive effects on the empowerment of women, leading to greater gender equality, as well as a reduction of poverty among vulnerable groups (REN21 2017). Energy services are crucial for the improvement of livelihood conditions by meeting basic needs; there is a link between modern energy and poverty. This led to considering electricity as the main component within development rural programmes (Mandelli et al. 2016).

In general, the deployment of renewable energy has led to additional economic benefits around the world. Africa can benefit from innovations and local value creation. Compared to fossil energy technologies, renewable-based technologies provide more employment opportunities due to higher labour intensity (Quitzow et al. 2016), creating jobs in rural areas

(German Advisory Council on Global Change 2009b). The share of local value creation relative to project costs will increase, as technology costs continue to decrease. In addition, energy infrastructure makes it possible to build a manufacturing sector, thus attracting further investment. In order to achieve this, several African countries implemented local content requirements[3] in their support policies. Most importantly, the emerging innovation of off-grid systems can lead to the creation of important economic and entrepreneurial opportunities for African companies (including PAYG) (Quitzow et al. 2016). For example, extended opening hours enabled by lightning, as shown in Figure 4, or the diverse income generation possibilities of a business owner in Uganda explained in Figure 5.

Figure 4 Lights are used to extend opening hours of a shop

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[3] Local content requirements require companies to use domestically manufactured goods or domestically supplied services in order to operate in an economy (OECD 2016).

Figure 5 The 500 W solar system powers a home, a public broadcasting system, a barbershop and a video hall in a rural village in Uganda.

Other income generating opportunities may include coordination with suppliers and distributors (mobile phone), preservation of fresh products for sale on weekly markets (fridge), unburdening from time-consuming tasks usually performed by women (grinding/milling/husking). Despite this, income generation is not an objective of most rural electrification initiatives (Hirmer & Guthrie 2017).

The communication of the previously discussed benefits of energy access is important, as electrification needs to be supported by the community in order to succeed. If projects are not tailored to what end-users value, benefits may be lost. For the reduction of poverty, it is essential to move beyond the provision of lighting and mobile phone charging and enable additional energy appliances, like television, street lighting or grain mills for household use, community service and productive uses (Hirmer & Guthrie 2017). Especially SHS have been criticised for not fulfilling the needs of productive uses or educational activities and thus offering a limited contribution to poverty reduction (Yadoo & Cruickshank 2012). The widespread pico-solar systems must be seen as a stepping stone on the path to electrification, as the improvement of the quality of life for households beyond the basics will need more electricity that such a system can supply. Much higher levels of electricity supply are required to reduce household chores and enable other benefits (IEA 2017a). That is why the development of mini-grids is often favoured over stand-alone solutions (Yadoo & Cruickshank 2012).

Community Renewable Energy

Distributed energy systems offer the opportunity for community participation, which can improve the long-term success of distributed energy projects. Through the empowerment and creation of local participation during planning and execution of those projects, local stakeholders are enabled to monitor and manage resources to improve investment decisions.

Community-based approaches are a valid alternative to a government- or market-based provision of energy. However, it is recommended to establish institutions to facilitate discussions among stakeholders (Guta et al. 2017). REN21 (2017) even call the old paradigm of energy access through grid connection obsolete, because hundreds of millions of households generate their own modern energy through off-grid systems or community-scale mini-grids motivated by a bottom-up customer demand. As published by the Alliance for Rural Electrification (2011), it is proven that the implementation of mini-grids leads to a positive social impact, as local governance structures are fostered and improved by the involvement of the community in the decision-making process.

Policy Uncertainty

Most significantly, the biggest obstacle for distributed systems is the policy uncertainty about off-grid electrification in national strategies, policies and regulations (Brent 2016; REN21 2017). Quitzow et al. (2016) identified that over the past decade, most African countries established policies for the promotion of renewable energy sources, however, these legal and regulatory frameworks often remain inconsistent or incomplete. Tax exemptions for renewable energy technologies may exclude related accessories or may be limited to import duties. This is supported by REN21 (2017), that name subsidies on kerosene and diesel as well as fiscal and import barriers (e.g. high import tariffs and VATs) as challenges, because both might significantly increase the price of products (compared to the conventional ones). Distributed renewable companies struggle to find capital due to the perceived policy risk that discourages investors. Accordingly, Brent (2016) demands a policy framework that is de-risking financing to achieve energy access for all.

Other challenges in the political field may be lengthy processes of legislation, institutional capacity deficits and a lack of clear division of responsibilities between different government agencies (Quitzow et al. 2016). Policy and market reforms might also be impeded by political economy challenges. Self-interest in the fossil-based energy sector and an unwillingness to change existing business models and practices might lead to a resistance to change by policy makers. As a consequence, the diversion of subsidies is difficult (Quitzow et al. 2016). Nevertheless, policy and regulatory changes can have a transformative effect on energy access and may result in a rapid provision of distributed renewable energy (Brent 2016). As shown earlier (see p. 19), several countries implemented policies and strategies to support rural electrification.

Technical Barriers, Modularity and Flexibility

Even though Rachel Kyte, the Chief Executive Officer of SEforALL and Special Representative of the UN Secretary-General for Sustainable Energy for All, says that ‘policy and finance have to catch up with technology’ (Brent 2016), renewable energy deployment in Africa faces several technical barriers. For example, there is often only limited and scant data on renewable energy resource availability, like solar radiation levels or wind speed (Quitzow et al. 2016). In order to tackle this issue, the International Renewable Energy Agency (IRENA) coordinated the Global Atlas for Renewable Energy initiative (IRENA 2018a). Among other, this initiative administrates a web platform that offers maps of renewable energy resources (IRENA 2018b). According to Quitzow et al. (2016), the initiative has improved the convergence and availability of data in many regions, although deficits remain.

REN21 (2017) further names a lack of product standards that allow the sale of low quality and counterfeit products as barriers for the development of decentralised renewable energy systems. In addition, there is a lack of qualified and skilled workforce to support the development of the sector (Guta et al. 2017; REN21 2017). Inadequate local technical skills often cause contracts with foreign technology providers for after-sales service, operation and maintenance (Quitzow et al. 2016). As a consequence, local value creation might get lost.

One of the main opportunities of distributed energy systems are modularity, flexibility and rapid construction time (REN21 2017). The satisfaction of the current and future energy demand is a tremendous challenge for the African continent, especially in light of population and economic growth (Quitzow et al. 2016). The African population is the fastest growing in the world, with an estimated 300 million young people reaching employment age in the next 15 years, two-thirds of whom live in rural areas (IEA 2017a, p. 76). In general, renewable energy projects come with the major advantage of relatively short lead times. This is crucial, as providers are not able to keep up with the ever-rising electricity demand in African countries (Quitzow et al. 2016). Off-grid systems can be scaled up to match the desired energy consumption and in case power demand increases. There are innovative products on the market that couple stand-alone generation with appliances. Mini-grids can also be scaled up with rising demand (IEA 2017a) and operation, with possible connection to a main grid (REN21 2017).

Costs and Financing

Although there are diverse efforts to finance distributed energy development (see p. 16), customers and companies may lack access to finance. Quitzow et al. (2016) name cost recovery as a particular challenge for rural electrification efforts because the costs for electricity supply in rural areas are usually higher than national averages. Many consumers are unable to pay the, in some cases significant, upfront costs of distributed systems. For companies, a lack of working capital may limit market development (Brent 2016). A major barrier for investment can be the lack of flexibility among electricity regulators to allow cost-covering tariffs in addition to uncertainty about the actual demand for electricity. Quitzow et al. (2016) name the introduction of PAYG schemes as a mitigation strategy.

Distributed renewable electricity supply is preferred for the remotest locations, because costs for transmission and distribution make main grid extension unfeasible. Areas that are not yet electrified have very low demand and load factors, making small-scale generation very well suitable (Mandelli et al. 2016). From a system cost perspective, off-grid systems may be the most cost-effective solution for energy supply in sparsely populated areas. Upfront costs can nevertheless be a critical barrier, which is why the availability of financing is important. Compared to mini-grids and on-grid systems, the levelled cost of off-grid systems is currently the highest. Falling costs for solar PV and batteries (IEA 2017a) might change this situation in the near future. Qoaider & Steinbrecht (2010) summarise that PV systems offer economic advantages compared with diesel generation systems, whereas the findings of Szabó et al.

(2011) show that this depends on the local and country specific conditions, as subsidies play a crucial role. REN21 (2017) state that renewables are already the most economical solution for off-grid electrification in many rural areas due to significant cost reductions in recent years. Compared to many grid markets, distributed systems offer cost savings. This is backed by Quitzow et al. (2016), who state that there is a consensus that these are cost-effective and quick to provide basic level electricity access (such as lightning and small electronic devices) on a small off-grid solution on PAYG basis. Particular SHS are cost-competitive with the grid in many African countries. Compared with kerosene lanterns, they offer better quality lighting at equal or lower cost (IRENA 2016; REN21 2017).

If higher levels of service are needed, for example for productive purposes, hybrid mini-grid systems based on diesel generation in combination with renewables are a cost-effective alternative to expansion of the grid (IRENA 2016; REN21 2017). Also the IEA (2017a) see mini-grid systems as commonly the least costly option for rural electrification, depending on the distance of the existing grid and the targeted area. Mini-grids can be used in densely populated areas with a small per-household demand, where a large number of households and businesses provide a sufficient load to justify the costs of the mini-grid development (REN21 2014). Hybrid mini-grid systems that are based on renewable energy offer significant cost savings compared to diesel-based systems. There is a certain demand threshold needed in order to justify the initial investments in the mini-grid network. Their installation therefore benefits from loads from public services, industrial or commercial facilities (IEA 2017a, p. 41). According to IEA (2017a, p. 40), levelled cost of electricity through mini-grids is higher than a main transmission and distribution network system.

If the option of connection is available, the IEA (2017a) states that grid extension enables the lowest costs to supply households with electricity. In contrast to that, REN21 (2014) reports that centralised grid systems fail to reach millions of people in rural and remote locations in developing countries. The power distribution cost, rather than the power production cost, accounts for the major share of the consumer end price (Kaltschmitt, Schröder & Schneider 2007). Transmission and distribution related costs, as well as the nature risk of large scale plant investments are avoided by the installation of distributed energy systems (Mandelli et al. 2016). It can be summarised that, as suggested by Szabó et al. (2011), a detailed investigation of the specific local conditions is required in order to determine the economic potential of the respective technology.

Energy efficiency plays an important role in driving energy access. Even if high-efficient appliances may cost more than less-efficient alternatives, their higher cost are compensated by the lower upfront cost of the energy system, as a smaller system is less costly. If the amount of energy that is required to provide modern energy services is reduced, the economics of energy access are better (REN21 2017). The use of currently available energy efficiency measures could cause the supply of universal access to modern energy services with using 50 - 85 % less energy than prevailing estimates state is required (REN21 2017, p. 102). For example, pico-PV systems decrease in size due to efficiency improvements. Therefore, energy efficiency enables distributed renewable energy systems the provision of energy services that otherwise might be economically or technically infeasible. In case of LED technology, energy efficiency has led to dramatic advancements in energy access efforts with falling costs of LED technology droving growth in the off-grid lighting market (REN21 2017).

In a scenario by the IEA (2017b) it is predicted that in order to reach full access to electricity, distributed systems combined with highly efficient appliances play a major role (Sustainable Development Scenario). More information on future predictions can be found in the World Energy Outlook 2017 published by IEA (2017b).

Energy Security

The use of distributed renewable systems and integration of renewable energy technologies into existing mini-grids can decrease the dependence on imports of fossil fuels (Mandelli et al. 2016; REN21 2017), thus reducing the vulnerability to fluctuation of global fossil prices and instability of supply. Moreover, the deployment of renewable energy systems substitutes imports and reduces expenses (Quitzow et al. 2016). Rising oil prices make the often used kerosene lamps unaffordably expensive for many people (German Advisory Council on Global Change 2009b). Distributed renewable systems also offer predictable prices and compared to centralised systems, reduce the vulnerability of the supply chain (Mandelli et al. 2016). Finally, the use of renewable energy sources minimises environmental impacts of electricity generation (see p. 13).

Distributed renewable energy systems provide significant potential for the electrification of rural households that among other advantages result in improved health, enhanced education, a reduction of poverty and gender equality. Whereas political uncertainty and a lack of finance are major barriers to implementation, the systems' contribution to energy security, their reliability, flexibility, modularity and environmental sustainability are the driving forces for their expansion.

Conclusion

Distributed renewable energy systems provide unprecedented opportunities to accelerate the transition to modern renewable energy services in remote and rural areas. They offer significant opportunities for human development, as they have considerable potential for households, community services but also for productive uses.

However, they also face barriers and challenges, comprising financial, economic, political, institutional, technical and socio-cultural factors that may be interconnected. In comparison to fossil-based technologies, distributed renewable systems are mainly characterised by improved energy security, high modularity and flexibility. They offer a fast and in some cases cost efficient way for the electrification of rural areas. In addition, distributed renewable systems offer enormous environmental benefits. There is also the opportunity of community involvement during planning and execution that results in the long-term success of electricity projects.

In Africa, the predominantly used distributed renewable energy system is solar PV and further expansion is expected. Especially the widespread pico-PV systems offer hardly enough capacity to improve the living conditions of rural households beside basic needs. In order to enable further benefits of power supply, electricity systems should be oriented towards consumer needs.

Based on the analysed literature, it can be summarised that future efforts should focus on the provision of financing for distributed renewable energy systems in Africa. Quality infrastructure, such as standardisation and certification for SHS should also be developed, as it might play a major role in enhancing confidence for investors and consumers. Lastly, increased funding for monitoring and evaluation of existing distributed systems as well as research and innovation is needed.

Picture Credits

Figure 1:

REN21 2017, Renewables 2017 Global Status Report, Renewable Energy Policy Network for the 21st Century, Paris, France, viewed 5 February 2018, <www.ren21.net/status-of-renewables/global-status-report/>.

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Figure 2:

Off Grid Electric mPower (Power Africa) <https://commons.wikimedia.org/wiki/File:Off_Grid_Electric_mPower_(Power_Africa)_(26542622422).jpg> is in the public domain.

Figure 3:

Drip Irrigation at Faylar Village, Senegal <https://commons.wikimedia.org/wiki/File:Drip_Irrigation_at_Faylar_Village,_Senegal.jpg> by InnoAfrica is licensed under the Creative Commons Attribution-Share Alike 4.0 International license <https://creativecommons.org/licenses/by-sa/4.0/deed.en>.

Figure 4:

Off Grid Electric mPower (Power Africa) <https://commons.wikimedia.org/wiki/File:Off_Grid_Electric_mPower_(Power_Africa)_(26542622352).jpg> is in the public domain.

Figure 5:

SunFunder SolarNow Uganda Aerial Drone Photos 405 <https://commons.wikimedia.org/wiki/File:SunFunder_SolarNow_Uganda_Aerial_Drone_Photos_405_(18337194273).jpg> is in the public domain.

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