## 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 minigrid 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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## 1 Introduction

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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).

15 Whereas past efforts mainly concentrated on centralised strategies (grid extension) in order 16 to provide electricity, distributed electricity approaches increasingly gained momentum in 17 recent years (Mandelli et al. 2016). However, the characteristics and benefits of distributed 18 energy systems for electricity supply are often not known – a gap this literature review tries to 19 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.

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## 32 Current Status in Africa

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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



- 1 that area (IEA 2017a, p. 80). South Africa is the outlier as it accounts for almost half of the
- 2 power generation capacity on the sub-continent (IEA 2014; Quitzow et al. 2016).



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

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5 The electrification rates in sub-Saharan Africa show that access is particularly low in rural 6 areas, with 80 % of those without access to electricity living in rural areas. The electrification 7 rate of rural areas is lower than 25 %, compared to 71 % in urban areas (IEA 2017a, p. 80). 8 This places a heavy burden on rural dwellers, as electricity access is a prerequisite for human 9 development. It comprises education opportunities and health, but also affects agricultural or 10 economic activities, as well as access to improved water resources and sanitation. At the same 11 time, Africa will be one of the continents most affected by climate change and many countries 12 will experience exacerbated water scarcity, health and food security risks (Quitzow et al. 13 2016).

Another significant obstacle that is often connected to missing electrification is the lack of clean 14 15 cooking facilities<sup>1</sup>. Worldwide 2.7 billion people (38 % of the global population) are affected 16 (REN21 2017, p. 98). In Africa, the vast majority of the affected population (792 million 17 people) is primarily concentrated in sub-Saharan Africa (REN21 2017, p. 99). As a 18 consequence, the main share of the population of sub-Saharan African countries lacks access 19 not only to electricity, but also clean cooking facilities. Almost 80% of the population of sub-20 Saharan Africa relies predominantly on solid biomass for cooking (IEA 2017a, p. 91). The 21 dependency on biomass for cooking comes with severe health, social and environmental 22 consequences. Each year, more than half a million premature deaths can be attributed to 23 indoor air pollution caused by cooking in sub-Saharan Africa. On average, a household 24 spends two hours for the collection and transport of firewood (IEA 2017a, p. 94). In some 25 countries, for example Sierra Leone, this number goes up to five hours per day (IEA 2017a, 26 p. 27). Mainly women and children are responsible for the provision and preparation of fuel, 27 suffering most from detrimental health conditions and other drawbacks, as a huge amount of

<sup>&</sup>lt;sup>1</sup> 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).

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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.

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### 10 Pathways to Rural Electrification

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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.

14 On-grid systems provide electricity through a connection to a local network that is linked to a 15 transmission network (IEA 2017a). For most people around the world, electricity is provided by 16 the electric grid, consisting of a large-scale integrated generation, transmission and 17 distribution network (REN21 2014). Power is generated in large, centralised power plants 18 using coal, natural gas, nuclear power, hydropower or solar energy as the energy source (IEA 19 2017a). However, decentralised generation can also be connected to the transmission network 20 at low voltage (e.g. solar photovoltaic (PV) units). In order to supply rural areas, an existing 21 grid is often extended beyond urban and peri-urban areas (REN21 2017). Especially in 22 remote, scarcely populated areas in developing countries, grid connection is hindered by high 23 investment costs for power distribution infrastructure in conjunction with low power demand 24 (Sauer, Rau & Kaltschmitt 2007).

25 Mini-grids are localised power networks that do not transmit electricity beyond the area of 26 service (IEA 2017a). They vary in size and are not connected to the transmission network, but 27 have an independent distribution network (REN21 2014). They are commonly installed in 28 remote areas to provide electricity to a relatively small number of concentrated located 29 customers, usually a group of households and businesses (REN21 2017). In order to gain a 30 stable flow of power that is required for all grid systems to work properly, mini-grids often 31 use either a small diesel generator or battery systems for back-up (IEA 2017a). Mini-grids are 32 based on modular generation technologies such as solar PV, wind turbines, small-scale 33 hydropower and diesel generators (IEA 2017a). In some cases, connection of mini-grids to 34 main networks is possible, if compatible. Usually mini-grids provide small-scale generation of 35 10 kW to 10 MW, whereas micro-grids offer a capacity range of 1-10 kW. However, there 36 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.

42 Although all three described electricity systems may have distributed components, only mini-43 grid and off-grid solutions are usually categorised as distributed energy systems. This term is 1 preferred by several authors, such as Ackermann, Andersson & Söder (2001), Pepermans et 2 al. (2005) or REN21 (2014), whereas other authors, such as IEA (2017b) use the term

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3 'decentralised' systems.

4 According to REN21 (2017), distributed energy systems are characterised by either one of the 5 following two conditions:

- 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.
- 8 9

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).

16 Distributed energy systems already provide electricity to millions of people (REN21 2017). 17 Especially in areas that have not yet been reached or are too expensive to electrify by grid 18 connection, their numbers continue to increase annually. Small-scale off-grid electricity 19 generation technologies can be used as a first step in the electrification process or as a 20 building-block for future grid development (Mandelli et al. 2016). They can serve as a 21 complement to or substitute of centralised energy generation systems (REN21 2017). 22 Governments in sub-Saharan Africa rely on electrification through grid extension with an 23 increasing share of renewable energy sources (IEA 2017a). The next chapter will present 24 technologies for distributed electricity generation.

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# Renewable Electricity Generation Technologies for Distributed Energy Systems 27

28 Energy systems based on fossil fuels have adverse impacts on the environment. The combustion 29 of fossil fuels (oil, gas, coal, peat) releases emissions into the environment that cause climatic 30 changes, air pollution and adverse effects on human health. Worldwide, electricity and heat 31 production was responsible for a share of 25 % of global greenhouse gas emissions in 2010. 32 Therefore, electricity generation is a major driver of anthropogenic climate change and its 33 resulting impacts on natural and human systems, such as increasingly frequent extreme 34 weather events (Victor et al. 2014, p. 123). International environmental conventions target the 35 reduction of greenhouse gas emissions, such as the United Nations Framework Convention on 36 Climate Change (Bruckner et al. 2014). Moreover, combustion processes cause emissions of 37 nitrogen and sulphur oxides as well as of other pollutants. The recovery and transport of fossil 38 energy resources causes further pollution, effects on soils and ecosystems. In addition, the 39 finiteness of fossil primary energy resources is also a driver for renewable energy sources 40 (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).



significantly reduced adverse impacts on the environment compared to fossil fuel or nuclearenergy generation.

Although the entire African continent makes up about 1 % of the world's CO<sub>2</sub> 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.
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#### Photovoltaics

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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).

30 Pico-PV systems comprise the smallest distributed solar PV systems. These systems usually 31 consist of a solar panel, a battery, one or more LED lamps and in many cases a mobile phone 32 charging port (IEA 2017a). Generally, they have a power output of 1-10 W (REN21 2017, 33 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 34 35 2016, more than 7.5 million pico-PV systems were sold worldwide. This represents 94 % of all 36 off-grid solar product sales (REN21 2017, p. 100). However, it needs to be kept in mind that 37 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

42 SHS for lighting and mobile phone charging.



1 2

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

3 Additionally, non-domestic applications are possible, such as powering water pumping, cooling

4 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

14 available for operating the pump (see Figure 3).





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2 **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).

8 There are two main limitations of PV electricity generation based on the presence of sunlight. 9 Firstly, the quantity of sunlight reaching the Earth's surface is not constant. The amount of 10 sunlight varies depending on location, time of day, season and weather conditions. Secondly, 11 the amount of sunlight reaching a certain area of the Earth's surface is relatively small. In 12 order to gain a larger amount of energy, a larger surface area is required (EIA 2017e). 13 Consequently, the largest amount of electricity is generated when PV cells and modules are 14 directly facing the sun. Tracking systems can be used to move the modules constantly facing 15 the sun. However, these systems are expensive. Instead, many PV systems have fixed modules 16 with an angle of inclination that further optimises performance (EIA 2017a).

17 In recent years, off-grid solar energy (pico-solar and solar home systems of less than 100 W) 18 has been one of the fastest growing industries in the provision of electricity access (Orlandi, 19 Tyabji & Chase 2016; REN21 2017). In 2016, nearly 8.2 million off-grid solar systems were 20 sold worldwide. That represents an increase of 41 % compared to 2015. In 2016, sales were 21 the highest in sub-Saharan Africa, although they decreased in that region by about 1 million 22 compared to 2015. India is the key market, followed by Kenya, Ethiopia, Uganda and 23 Tanzania. In 2016, Eastern Africa accounted for an estimated 70 % of sales of pico-PV and 24 SHS in sub-Saharan Africa. More than 30 % of people living off the grid in Kenya have a 25 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.

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#### Wind Power

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6 Wind power uses kinetic energy from moving air. The blades of wind turbines are caused to 7 run because of the wind flowing over the blades, creating a lift. The blades are connected to 8 a drive shaft that turns an electric generator that produces electricity (EIA 2017b). Small-scale 9 wind turbines are in most cases coupled with a battery and a battery charge regulator 10 (Kaltschmitt, Skiba & Wiese 2007) and provide electricity for farms, homes and small 11 businesses, water pumping and telecommunication (Kaltschmitt, Skiba & Wiese 2007; REN21 12 2017).

Several definitions of small wind turbines exist. Technically, the standard IEC 61400-2 defines 13 14 a rotor swept area of less than 200 m<sup>2</sup>, equating to a rated power of approximately 50 kW 15 generating at a voltage below 1,000 V AC or 1,500 V DC (WWEA 2017, p. 10). A rotor 16 swept area of 200 m<sup>2</sup> equals a rotor diameter of about 16 m. However, the differentiation of 17 small wind power is depending on the country (WWEA 2017). Several authors (Kaltschmitt, 18 Skiba & Wiese 2007; WWEA 2017) use an upper nominal capacity limit of 100 kW in their 19 definitions. This limit is mainly based by the leading role of the North American and European 20 markets (WWEA 2017, p. 10). The Alliance for Rural Electrification (2011, p. 18) states that 21 most small-scale wind turbines in rural areas have a diameter of up to 7 m and a power 22 output between 1kW and 10 kW. In case of rural household supply, even wind turbines below 23 a diameter of 2 m and with a 1kW output can be used (Alliance for Rural Electrification 2011, 24 p. 18).

25 In order to properly operate a small wind turbine, careful planning is required. Wind is 26 always in a non-steady state due to the wide temporal and spatial variations of wind velocity 27 (Omer & Omer 2007). Accordingly, an adequate location of the wind turbine is a key 28 requirement for successful small-scale wind power projects and should be carefully studied. 29 Wind measures might be necessary prior to installation. However, in relation to the output and 30 added value of the wind turbine, long-term wind studies are often too time consuming or costly 31 and therefore often avoided by project developers (Alliance for Rural Electrification 2011). In 32 addition, wind data is very sparsely collected in Africa, which makes not only the development 33 of wind energy difficult, but also hinders the reduction of detrimental effects of wind and 34 related drifting sand in building activities, agriculture and wind-related disasters, such as 35 erosion or fire (Wisse & Stigter 2007). Generally speaking, wind speed increases with 36 altitude and over open areas without windbreaks. The tops of smooth, rounded hills, open 37 plains and water and mountain gaps that funnel wind are therefore good sites for installation 38 (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).

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#### Hydropower

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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.

7 In regard to hydropower, a distinction is drawn between small-scale and conventional, large 8 hydropower plants. However, these are not competing components of the hydropower sector, 9 as small-scale hydropower plants are, among other aspects, mainly located in smaller rivers 10 (Couto & Olden 2018). In contrast to conventional hydroelectric power plants, they exhibit 11 little to no water storage capacity, making locations with steady flow the most suitable for 12 those systems. Furthermore, areas with an elevation drop, high annual precipitation rates and 13 catchment areas with a supply of water into the rivers offer best resources (Alliance for Rural 14 Electrification 2011).

15 The classification small-scale hydroelectric power is used frequently, but is often not further 16 defined. Similar to the discourse on defining small-scale wind power systems (see p. 10), 17 definitions are often based on generation capacity and vary substantially. The generation 18 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).

35 In addition to this significant variation in definitions and wide range of scales of capacity 36 across countries, the design of small-scale hydropower plants is also diverse. There might be 37 significant differences in dam sizes, reservoirs, storage capacity, outlet structure or plant 38 operation (Couto & Olden 2018). The technology of a hydropower system can be categorised 39 into run-of-river, reservoir-based capacity and low-head in-stream technology (REN21 2017). 40 Turbines are the most expensive part of a small hydroelectric power station. The Alliance for 41 Rural Electrification (2011, p. 23) gives an overview on the most important types of hydro 42 turbines and generator types. For a more detailed description about turbine layouts and 43 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

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3 pumping (REN21 2017).

4 Beside the choice of the system, the plant's layout and surroundings are a major concern in 5 planning, as hydropower particularly has a higher interaction with its environment than other 6 power systems. Sound knowledge of the site's geomorphology and hydrology are necessary in 7 order to predict the availability and time distribution of flow rates. This expertise should 8 include the maximum flood of the river to avoid any damages. Proven specialists are 9 recommended for flow rate evaluation and environmental engineering should be involved for 10 the assessment of landslides, instability and other factors, such as fish migration (Alliance for 11 Rural Electrification 2011).

12 Hydroelectric power is significantly the world's primary source of renewable electricity, with a 13 share of 16.6 % of global electricity production in 2016 (REN21 2017, p. 33). Although 91 % 14 of all hydroelectric power plants are considered as small-scale plants, they contribute to just 15 11 % of the global electricity generation capacity of hydroelectric power (Couto & Olden 16 2018, p. 93). The latest World Small Hydropower Development Report gathers information 17 on the status quo, future potential, policies and barriers for small hydro development for each 18 country (see UNIDO & ICSHP 2016). According to this report, in 2016 the globally installed 19 small-scale hydropower (smaller than 10 MW) capacity was about 78 GW (UNIDO & ICSHP 20 2016, p. 7). The African continent has an installed small-scale hydroelectric power capacity of 21 580 MW and considerable potential for development (UNIDO & ICSHP 2016, p. 12).

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#### **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).

36 Although it is technically possible to use bioenergy-based technologies in rural areas (German 37 Advisory Council on Global Change 2009b), Mandelli et al. (2016) do not suggest their 38 usage, mainly due to the fact that the minimum plant size for electricity production does not fit 39 stand-alone, but rather micro-grid scale and that significant concerns regarding sustainability 40 arise if used in rural areas. Other authors, such as the Alliance for Rural Electrification (2011), 41 IEA (2017a) or REN21 (2017), also do not list bioenergy technologies for electricity supply in 42 rural areas. Nevertheless, energy from biomass is primarily used for cooking and heating 43 purposes in rural areas.

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#### 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).

10 Different configurations of hybrid systems exist. The simplest technology is to couple a 11 renewable energy technology, e.g. solar PV, with a traditional, resulting in a PV-diesel system. 12 More complex is the combination with a storage technology, e.g. a wind-diesel-battery system 13 (Mandelli et al. 2016). Renewable energy hybrid systems combine two or more renewable 14 power technologies (REN21 2017). Particularly if the site offers both, sufficient solar radiation 15 and above-average wind conditions, wind-battery systems may be combined with PV modules 16 to wind-battery-PV systems (Kaltschmitt, Skiba & Wiese 2007). Wind energy converters and 17 solar energy systems complement each other well on many locations with regard to seasonal 18 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 minigrid (REN21 2014, p. 101).

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#### 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.

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#### 39 Environmental Impacts

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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.

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#### Key Impacts of Distributed Renewable Energy Technologies

6 Regarding PV systems, environmental impacts are primarily related to the manufacturing of 7 solar cells. The main areas of concern are the consumption of scarce mineral resources and the 8 toxicity of used chemicals. The specific effects are largely dependent on the type of solar cells 9 used for the PV system (mono-crystalline cells, multi-crystalline cells, ...) (Kaltschmitt, Schröder & 10 Schneider 2007). A more detailed analysis of these severe effects is provided by Kaltschmitt, 11 Schröder & Schneider (2007, p. 292). Recycling of solar cells is still at its infancy and 12 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 13 14 recycling infrastructure planning reaches remote areas. In addition to these effects, it needs to 15 be kept in mind that ground-mounted PV systems partly or entirely inhibit the use of ground 16 (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.

23 Inappropriate planning and design of hydropower plants can have negative effects on the 24 environment (UNIDO & ICSHP 2016). Couto & Olden (2018) even state that there is scientific 25 evidence that indicates substantial environmental impacts of small hydropower plants . As 26 discussed earlier in this paper (see p. 11), there is a significant variation in country-specific 27 classifications of small hydropower plants based on their generation capacity. Consequently, 28 there are varying small power plant layouts that are strongly correlated with their 29 environmental impacts. In addition to that, the diversity of operation modes and sizes of small 30 hydropower plants produce a variety of ecological consequences. These may not necessarily 31 vary from those expected for large hydropower plants. The magnitude of impacts depends on 32 the attributes of specific projects and their landscape context. However, these impacts are 33 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 34 35 magnitude of their environmental impacts caused by the diversity of sizes and operation 36 modes. The emphasis of 'small' in small hydro policies is equated with negligible environmental 37 impacts (Couto & Olden 2018). Most importantly, there are three areas that cause 38 environmental effects during small hydropower operation: impoundments, barrier effects and 39 diversion effects. These may result in a loss in biodiversity, interrupted migration of fish, 40 change in the composition of species (including mammals, birds and amphibians because of the 41 changed food availability), effects on ecosystems in the lower course of a river, limited 42 reproduction of certain types of fish, isolation of various fish populations or the reduction of 43 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).

3 The main discussion in the field of bioenergy concentrates on the competition in the cultivation 4 of food and energy crops for the available land, but also for the available water. This 5 discussion is rather complex and cannot be fully portrayed here, however, a detailed analysis 6 of the topic is given by the German National Academy of Sciences Leopoldina (2012) and 7 German Advisory Council on Global Change (2009b). Energy crop cultivation may displace 8 existing food production, with the consequence that food production must be transferred to 9 other unspoiled areas. As an indirect consequence, forests may be cleared, sometimes even in 10 other countries and the loss of biological diversity may be further exacerbated. In addition, 11 there is already an increasing demand for land worldwide and predictions of the Food and 12 Agriculture Organization of the United Nations foresee a rising demand for land for food 13 production for the increasing world population. Conflicts over land can be one consequence 14 (German Advisory Council on Global Change 2009a). Mandelli et al. (2016) see a 15 sustainable use of bioenergy for power generation as quite difficult in rural areas, because of 16 the complexity of the supply chain and thus the required local capacity and very specific and 17 comprehensive analysis at the local level. Additionally, they claim that many countries lack 18 institutional structures in order to support the development of new bioenergy technologies (i.e. 19 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.

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

34 The water, energy, food nexus is a concept that is increasingly recognised. It emphasises the 35 interconnections and interdependencies between water, energy and food supply (Hoff 2011; 36 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 37 38 pumping, irrigation, mechanised agriculture, processing of harvest, transportation (IRENA 39 2015) and mineral fertiliser production (Bernstein Lenny et al. 2007). At the same time, poor 40 agricultural practices lead to soil erosion, deforestation and negatively affect the availability 41 and quality of water resources. There is a competition for land and water resources between 42 energy and food production activities that might lead to food-fuel tradeoffs. Particularly for 43 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).

3 Hoff (2011) outlines a considerable overlap between the people without appropriate access 4 to water, the ones who are undernourished and those without access to electricity. The nexus 5 approach offers perspectives on the implementation of integrated solutions for the 6 management of environmental impacts and allows a holistic understanding of unintended 7 consequences of policies, technologies and practices. It represents a multi-dimensional means 8 for the description of the complexity and nonlinearity of interactions of humans and 9 environment (Kurian 2017). Consequently, the nexus affects the extent of the simultaneous 10 achievement of water, energy and food security objectives, making it a major consideration in 11 the sustainable development strategies of countries and forcing governments, the private 12 sector, communities, the academic world and other stakeholders to investigate integrated 13 solutions to ease the pressure and to formulate development strategies based on a sustainable 14 and efficient use of scarce resources (IRENA 2015).

15 Renewable energy technologies can address some of the trade-offs between water, energy 16 and food and bring significant benefits in all three sectors. Compared to conventional energy 17 technologies, renewable energy technologies can reduce the competition by providing less 18 resource-intensive processes and technologies. Especially distributed renewable energy 19 technologies can offer integrated solutions for expanding access to sustainable energy while 20 at the same time ensuring security of supply across the three sectors (IRENA 2015). According 21 to Stevens & Gallagher (2015), improved energy access, low external input and agro-22 ecological approaches offer the best opportunities for sustainability. Successful connection with 23 local market systems for the produced crops and products is required to maximise the benefits 24 regarding poverty reduction.

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### 26 Realisation of Distributed Renewable Energy Systems

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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.

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#### Investments

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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).



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#### Private Sector Engagement and Business Models

11 In order to meet Africa's investment needs in the energy sector, significant private sector 12 engagement is crucial. Substantial efforts have been made in a number of countries to 13 improve the role of independent power producers. Currently, the market for SHS and other 14 off-grid renewable energy services is experiencing a rapid expansion lead by the private 15 sector. What is more, there is an increasing trend of international private equity targeting the 16 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.

23 These business models have been revolutionised by technological advances. For example, it is 24 becoming increasingly common to pay for energy services via smartphone (REN21 2017). In 25 some sub-Saharan African countries, more households own mobile phones (more than a quarter 26 are smartphones), than have access to electricity. This helps to increase access to a large array 27 of energy services in rural areas. Especially in East Africa, digital mobile-enabled platforms 28 and mobile money are used for the distribution of decentralised energy systems. More and 29 more companies target areas without electric connection, but with mobile phone reception (IEA 30 2017a).

31 The PAYG model will be further described in the following. In addition to regular fixed 32 payments through mobile money services via phone, customers pay an upfront fee in exchange 33 for an energy product. This model is a rapidly growing energy access solution (REN21 2017). 34 The market leader, M-KOPA SOLAR, has connected about 600,000 households to solar power 35 systems in Eastern Africa. Some 500 new SHS were installed every day (M-KOPA SOLAR 36 2018; REN21 2017). However, criticism about their business model exists. Notably, in an 37 article published in Bloomberg Businessweek, Faris (2015) accuses M-KOPA SOLAR of making 38 profit off of poor Africans. Initially M-KOPA SOLAR sells SHS, but tries to sell more products 39 on instalment to the customer. Therefore M-KOPA SOLAR is rather a finance company trying to 40 build a long-term finance relationship by offering more products. To customers it might not be 41 clear that they enter a financial – and not a traditional retail relationship. The revenue of the 42 company located in Nairobi was USD 30 million in 2015, with an estimated doubling in 2016 43 and further growth plans (Faris 2015). In addition, the company can remotely monitor products



3 PAYG schemes offer the potential to enhance the scaling-up of off-grid renewable energy 4 services for customers with low and irregular incomes. At the same time, the local off-grid 5 industry can be expanded (Quitzow et al. 2016). These energy services are mostly active in 6 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 7 8 the distribution of renewable off-grid systems. Recently the Republic of Togo partnered with 9 the company BBOXX for the distribution of more than 300,000 SHS in Togo in the next 10 5 years (IEA 2017a).

11 For PAYG energy services mainly solar systems are used. The most popular is the installation 12 of SHS that consist of a solar module, a battery and small appliances, such as LED bulbs or 13 mobile phone chargers. On average, customers gain low levels of power, but if highly energy-14 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 15 16 productive uses (e.g. water pumping or agro-processing) and clean cooking (REN21 2017).

17 Investments in off-grid solar PV systems are dominated by investments in PAYG companies. For 18 example, during 2016 the Nigerian off-grid solar company Lumus Global raised 19 USD 90 million of funding through debt financing and equity to further develop its operations. 20 This is one of the largest amounts raised by a single company in one year in the entire sector (REN21 2017, p. 106). 21

22 Other, alternative funding mechanisms such as crowdfunding continued to promote the 23 development of small decentralised renewable energy system companies and initiatives. In 24 2015, USD 3.4 million were raised. Crowdfunding for clean cooking stoves in the private 25 sector is also gaining popularity (REN21 2017, p. 106).

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### Donor Initiatives and Programme Developments

29 All major bilateral and multilateral donor agencies actively support renewable energy 30 projects in Africa and have launched a significant number of new initiatives to support the 31 renewable energy sector in Africa. One example of the role of renewable energy in 32 international development cooperation is the UN Sustainable Energy for All (SEforALL) 33 initiative launched in 2011 (Quitzow et al. 2016). The initiative has three main objectives:

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- 1. to ensure universal access to modern energy services,

2. to double the global rate of improvement in energy efficiency and

36 3. to double the share of renewable energy in the global energy mix.

37 Key to this initiative is the development of Country Action Agendas that outline short- to 38 medium-term projects and programmes (Quitzow et al. 2016; SEforALL 2018). The SEforALL 39 platform brings various actors together in order to create effective coalitions and 40 partnerships. It focuses on capacity building in governments, organisations and private sector 41 actors (REN21 2017). In addition to SEforALL, major political initiatives exist on the regional 42 and sub-regional level. These support political dialogue between African countries and donor 43 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).

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#### **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).

10 Several countries also developed dedicated institutions to support renewable energy 11 development, such as the Centre for Renewable Energy and Energy Efficiency in Cap Verde 12 that promotes renewables (Quitzow et al. 2016). In 2016, the Nigerian Electricity Regulatory 13 Commission announced plans to finalise its mini-grid regulation, in order to streamline permit 14 and tariff procedures (REN21 2017).

15 Strategy plans are implemented in order to move away from the strategy of grid expansion 16 for rural electrification. More recently, policies were implemented by several countries for 17 decentralised approach of rural electrification based on renewable energy sources. For 18 instance, Uganda adopted the Rural Electrification Strategy and Plan of 2013-2022 that 19 includes support for community-based<sup>2</sup> 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 20 21 which 22 % will be through off-grid connections. Kenya implemented a Feed-in-Tariff in 2012 22 that includes solar mini-grid systems (Quitzow et al. 2016). Sierra Leone exempted all VAT 23 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).

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## 30 Opportunities and Obstacles of Distributed Renewable Energy for Rural

- 31 Electrification
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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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<sup>&</sup>lt;sup>2</sup> 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

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3 First and foremost, distributed energy systems significantly contribute to energy access. 4 Distributed renewable electricity systems provide affordable lighting and enhance 5 communication (REN21 2017; Trotter, McManus & Maconachie 2017), which has also a great 6 impact on improving the quality of education.

7 Globally, there are approximately 200 million children that attend primary and secondary 8 schools that have no access to energy services. Quality education is a key driver for 9 sustainable development. Access to electricity offers, for example, prolonged time for reading 10 and homework (lighting), access to information and knowledge (computer) and expanded 11 vocational offerings in engineering, welding, metalwork, carpentry (school laboratories and 12 workshops). The imbalance between rural and urban communities can be shifted by making 13 rural dwellers more competitive (Hirmer & Guthrie 2017). Teachers can also be attracted to 14 rural areas (Mandelli et al. 2016).

15 The ability to use the internet allows access to open source knowledge. For instance, Open 16 Source Ecology (2018) offers construction manuals for several machines. An example is Libre 17 Solar, an open hardware project currently with focus on solar electricity generation and 18 storage (Libre Solar 2018). An online step by step tutorial created by Collective Open Source 19 Hardware (2018) shows how a modular system can be set up, depending on power and 20 storage capacity requirements. Electrical circuit boards are interconnected between energy 21 producers (e.g. as solar panels), energy storage (e.g. lithium-ion batteries) and the load 22 (appliances such as a computer). The tutorial can be found at the Collective Open Source 23 Hardware (2018) website.

24 Access to electricity improves quality and availability of health services and well-being. A 25 reliable electricity service in health clinics and hospitals can significantly enhance a multitude 26 of health services, such as vaccinations (refrigerator/freezer), emergency response (mobile 27 phone), improved medical equipment, public health education (television, smart phones), night-28 time care and child delivery at night (lighting) (Hirmer & Guthrie 2017). Adair-Rohani et al. 29 (2013, p. 254) show that although 96 % of hospitals in Kenya have power supply, only 24 %30 have reliable electricity. In Kenya, 72 % of other health facilities are connected to electricity, 31 but only show 15 % reliability. These numbers emphasise that health care workers are often 32 forced to work with torches or polluting and dangerous kerosene lamps (Adair-Rohani et al. 33 2013). Another example among many is the installation of street lightning, which increases the 34 safety of communities, as injuries, animal attacks (e.g. snakes) or attacks of thieves can be 35 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





1 (German Advisory Council on Global Change 2009b). The share of local value creation 2 relative to project costs will increase, as technology costs continue to decrease. In addition, 3 energy infrastructure makes it possible to build a manufacturing sector, thus attracting further 4 investment. In order to achieve this, several African countries implemented local content 5 requirements<sup>3</sup> in their support policies. Most importantly, the emerging innovation of off-grid 6 systems can lead to the creation of important economic and entrepreneurial opportunities for 7 African companies (including PAYG) (Quitzow et al. 2016). For example, extended opening 8 hours enabled by lightning, as shown in Figure 4, or the diverse income generation possibilities 9 of a business owner in Uganda explained in Figure 5.



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

<sup>&</sup>lt;sup>3</sup> Local content requirements require companies to use domestically manufactured goods or domestically supplied services in order to operate in an economy (OECD 2016).





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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.

4 Other income generating opportunities may include coordination with suppliers and distributors 5 (mobile phone), preservation of fresh products for sale on weekly markets (fridge), 6 from time-consuming tasks usually performed unburdening by women 7 (grinding/milling/husking). Despite this, income generation is not an objective of most rural 8 electrification initiatives (Hirmer & Guthrie 2017).

9 The communication of the previously discussed benefits of energy access is important, as 10 electrification needs to be supported by the community in order to succeed. If projects are not 11 tailored to what end-users value, benefits may be lost. For the reduction of poverty, it is 12 essential to move beyond the provision of lighting and mobile phone charging and enable 13 additional energy appliances, like television, street lighting or grain mills for household use, 14 community service and productive uses (Hirmer & Guthrie 2017). Especially SHS have been 15 criticised for not fulfilling the needs of productive uses or educational activities and thus 16 offering a limited contribution to poverty reduction (Yadoo & Cruickshank 2012). The 17 widespread pico-solar systems must be seen as a stepping stone on the path to electrification, 18 as the improvement of the quality of life for households beyond the basics will need more 19 electricity that such a system can supply. Much higher levels of electricity supply are required 20 to reduce household chores and enable other benefits (IEA 2017a). That is why the 21 development of mini-grids is often favoured over stand-alone solutions (Yadoo & Cruickshank 22 2012).

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#### Community Renewable Energy

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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

5 generate their own modern energy through off-grid systems or community-scale mini-grids 6 motivated by a bottom-up customer demand. As published by the Alliance for Rural 7 Electrification (2011), it is proven that the implementation of mini-grids leads to a positive 8 social impact, as local governance structures are fostered and improved by the involvement of 9 the community in the decision-making process.

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#### Policy Uncertainty

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13 Most significantly, the biggest obstacle for distributed systems is the policy uncertainty about 14 off-grid electrification in national strategies, policies and regulations (Brent 2016; REN21 15 2017). Quitzow et al. (2016) identified that over the past decade, most African countries 16 established policies for the promotion of renewable energy sources, however, these legal and 17 regulatory frameworks often remain inconsistent or incomplete. Tax exemptions for renewable 18 energy technologies may exclude related accessories or may be limited to import duties. This 19 is supported by REN21 (2017), that name subsidies on kerosene and diesel as well as fiscal 20 and import barriers (e.g. high import tariffs and VATs) as challenges, because both might 21 significantly increase the price of products (compared to the conventional ones). Distributed 22 renewable companies struggle to find capital due to the perceived policy risk that 23 discourages investors. Accordingly, Brent (2016) demands a policy framework that is de-24 risking financing to achieve energy access for all.

25 Other challenges in the political field may be lengthy processes of legislation, institutional 26 capacity deficits and a lack of clear division of responsibilities between different government 27 agencies (Quitzow et al. 2016). Policy and market reforms might also be impeded by political 28 economy challenges. Self-interest in the fossil-based energy sector and an unwillingness to 29 change existing business models and practices might lead to a resistance to change by policy 30 makers. As a consequence, the diversion of subsidies is difficult (Quitzow et al. 2016). 31 Nevertheless, policy and regulatory changes can have a transformative effect on energy 32 access and may result in a rapid provision of distributed renewable energy (Brent 2016). As 33 shown earlier (see p. 19), several countries implemented policies and strategies to support 34 rural electrification.

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### 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.

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4 REN21 (2017) further names a lack of product standards that allow the sale of low quality 5 and counterfeit products as barriers for the development of decentralised renewable energy 6 systems. In addition, there is a lack of qualified and skilled workforce to support the 7 development of the sector (Guta et al. 2017; REN21 2017). Inadequate local technical skills 8 often cause contracts with foreign technology providers for after-sales service, operation and 9 maintenance (Quitzow et al. 2016). As a consequence, local value creation might get lost.

10 One of the main opportunities of distributed energy systems are modularity, flexibility and 11 rapid construction time (REN21 2017). The satisfaction of the current and future energy 12 demand is a tremendous challenge for the African continent, especially in light of population 13 and economic growth (Quitzow et al. 2016). The African population is the fastest growing in 14 the world, with an estimated 300 million young people reaching employment age in the next 15 15 years, two-thirds of whom live in rural areas (IEA 2017a, p. 76). In general, renewable 16 energy projects come with the major advantage of relatively short lead times. This is crucial, 17 as providers are not able to keep up with the ever-rising electricity demand in African 18 countries (Quitzow et al. 2016). Off-grid systems can be scaled up to match the desired 19 energy consumption and in case power demand increases. There are innovative products on 20 the market that couple stand-alone generation with appliances. Mini-grids can also be scaled 21 up with rising demand (IEA 2017a) and operation, with possible connection to a main grid 22 (REN21 2017).

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#### Costs and Financing

26 Although there are diverse efforts to finance distributed energy development (see p. 16), 27 customers and companies may lack access to finance. Quitzow et al. (2016) name cost 28 recovery as a particular challenge for rural electrification efforts because the costs for 29 electricity supply in rural areas are usually higher than national averages. Many consumers 30 are unable to pay the, in some cases significant, upfront costs of distributed systems. For 31 companies, a lack of working capital may limit market development (Brent 2016). A major 32 barrier for investment can be the lack of flexibility among electricity regulators to allow cost-33 covering tariffs in addition to uncertainty about the actual demand for electricity. Quitzow et 34 al. (2016) name the introduction of PAYG schemes as a mitigation strategy.

35 Distributed renewable electricity supply is preferred for the remotest locations, because costs 36 for transmission and distribution make main grid extension unfeasible. Areas that are not yet 37 electrified have very low demand and load factors, making small-scale generation very well 38 suitable (Mandelli et al. 2016). From a system cost perspective, off-grid systems may be the 39 most cost-effective solution for energy supply in sparsely populated areas. Upfront costs can 40 nevertheless be a critical barrier, which is why the availability of financing is important. 41 Compared to mini-grids and on-grid systems, the levelled cost of off-grid systems is currently 42 the highest. Falling costs for solar PV and batteries (IEA 2017a) might change this situation in 43 the near future. Qoaider & Steinbrecht (2010) summarise that PV systems offer economic 44 advantages compared with diesel generation systems, whereas the findings of Szabó et al.



1 (2011) show that this depends on the local and country specific conditions, as subsidies play a 2 crucial role. REN21 (2017) state that renewables are already the most economical solution for 3 off-grid electrification in many rural areas due to significant cost reductions in recent years. 4 Compared to many grid markets, distributed systems offer cost savings. This is backed by 5 Quitzow et al. (2016), who state that there is a consensus that these are cost-effective and 6 quick to provide basic level electricity access (such as lightning and small electronic devices) on 7 a small off-grid solution on PAYG basis. Particular SHS are cost-competitive with the grid in 8 many African countries. Compared with kerosene lanterns, they offer better quality lighting at 9 equal or lower cost (IRENA 2016; REN21 2017).

If higher levels of service are needed, for example for productive purposes, hybrid mini-grid 10 11 systems based on diesel generation in combination with renewables are a cost-effective 12 alternative to expansion of the grid (IRENA 2016; REN21 2017). Also the IEA (2017a) see 13 mini-grid systems as commonly the least costly option for rural electrification, depending on 14 the distance of the existing grid and the targeted area. Mini-grids can be used in densely 15 populated areas with a small per-household demand, where a large number of households 16 and businesses provide a sufficient load to justify the costs of the mini-grid development 17 (REN21 2014). Hybrid mini-grid systems that are based on renewable energy offer significant 18 cost savings compared to diesel-based systems. There is a certain demand threshold needed in 19 order to justify the initial investments in the mini-grid network. Their installation therefore 20 benefits from loads from public services, industrial or commercial facilities (IEA 2017a, p. 41). 21 According to IEA (2017a, p. 40), levelled cost of electricity through mini-grids is higher than a 22 main transmission and distribution network system.

23 If the option of connection is available, the IEA (2017a) states that grid extension enables the 24 lowest costs to supply households with electricity. In contrast to that, REN21 (2014) reports that 25 centralised grid systems fail to reach millions of people in rural and remote locations in 26 developing countries. The power distribution cost, rather than the power production cost, 27 accounts for the major share of the consumer end price (Kaltschmitt, Schröder & Schneider 28 2007). Transmission and distribution related costs, as well as the nature risk of large scale 29 plant investments are avoided by the installation of distributed energy systems (Mandelli et al. 30 2016). It can be summarised that, as suggested by Szabó et al. (2011), a detailed 31 investigation of the specific local conditions is required in order to determine the economic 32 potential of the respective technology.

33 Energy efficiency plays an important role in driving energy access. Even if high-efficient 34 appliances may cost more than less-efficient alternatives, their higher cost are compensated 35 by the lower upfront cost of the energy system, as a smaller system is less costly. If the amount 36 of energy that is required to provide modern energy services is reduced, the economics of 37 energy access are better (REN21 2017). The use of currently available energy efficiency 38 measures could cause the supply of universal access to modern energy services with using 50 -39 85 % less energy than prevailing estimates state is required (REN21 2017, p. 102). For 40 example, pico-PV systems decrease in size due to efficiency improvements. Therefore, energy 41 efficiency enables distributed renewable energy systems the provision of energy services that 42 otherwise might be economically or technically infeasible. In case of LED technology, energy 43 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). 44

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).

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#### Energy Security

8 The use of distributed renewable systems and integration of renewable energy technologies 9 into existing mini-grids can decrease the dependence on imports of fossil fuels (Mandelli et al. 10 2016; REN21 2017), thus reducing the vulnerability to fluctuation of global fossil prices and 11 instability of supply. Moreover, the deployment of renewable energy systems substitutes 12 imports and reduces expenses (Quitzow et al. 2016). Rising oil prices make the often used 13 kerosene lamps unaffordably expensive for many people (German Advisory Council on 14 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. 15 16 2016). Finally, the use of renewable energy sources minimises environmental impacts of 17 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.

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### 25 Conclusion

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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.

31 However, they also face barriers and challenges, comprising financial, economic, political, 32 institutional, technical and socio-cultural factors that may be interconnected. In comparison to 33 fossil-based technologies, distributed renewable systems are mainly characterised by 34 improved energy security, high modularity and flexibility. They offer a fast and in some cases 35 cost efficient way for the electrification of rural areas. In addition, distributed renewable 36 systems offer enormous environmental benefits. There is also the opportunity of community 37 involvement during planning and execution that results in the long-term success of electricity 38 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.



- 1 Based on the analysed literature, it can be summarised that future efforts should focus on the 2 provision of financing for distributed renewable energy systems in Africa. Quality
- 3 infrastructure, such as standardisation and certification for SHS should also be developed, as it
- 4 might play a major role in enhancing confidence for investors and consumers. Lastly, increased
- 5 funding for monitoring and evaluation of existing distributed systems as well as research and
- 6 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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