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From the Editors

Preface by Ruth Schaldach

This is the fourth volume of the RUVIVAL Publication Series. This open access publication series is developed within the e-learning project RUVIVAL, which you can always visit under www.ruvival.de.

Our project is part of an initiative by the City of Hamburg to establish together with all public universities in Hamburg the Hamburg Open Online University (www.hoou.de). The idea is to make the knowledge of universities not only available online for the broader public, but also to invite people to participate in the knowledge production and exchange.

RUVIVAL is dedicated to sharing knowledge necessary to face rising environmental challenges, especially in rural areas. Therefore, to empower people to restore and rebuild these areas by themselves. RUVIVAL collects practices and research conducted at the Institute of Wastewater Management and Water Protection (AWW) at Hamburg University of Technology (TUHH), but also from all over the world. Each contribution in this publication is connected to further interactive multimedia material, which can be found, read, tested, watched, shared and extended on the RUVIVAL website, sorted by topic into several toolboxes (https://www.ruvival.de/toolbox/).

Each volume of the RUVIVAL Publication Series takes on a topic, which represents a cornerstone of sustainable rural development. The approach draws a systematic and interdisciplinary connection between water, soil, nutrition, climate and energy. Measures which enable sustainable use of land resources and improvements of living conditions are reviewed and new ideas are developed with consideration of their different social, political and demographic contexts.

In Volume 4, you get informed on the worldwide challenges faced by energy shortages and lack of wastewater treatment. These topics are interconnected, obviously in regard to water logistics, where pumps are required to transport water, using often a lot of energy; or if the water is highly polluted, by using energy-intense wastewater treatment processes. However, both topics are also intertwined in less obvious ways, as no access to energy has also a severe impact on accessing education or being able to reach information. This can also affect a community in their ability to take, for example, action in regard to wastewater treatment measures by themselves. Both literature reviews collect also some decentralised solutions, which require more knowledge than capital.

The literature reviews are a small collection of normally three reviews, but this time two long reviews, written in collaboration with Master students, PhD students and researchers at the AWW Institute at Hamburg University of Technology. The work is supervised by at least one senior researcher at the AWW Institute, who is specialised in a related subject. The entire process entails several feedback rounds. This outcome is then published on the RUVIVAL webpage as a working paper and the broader audience is asked to participate with further feedback or ideas in our RUVIVAL

Community (https://www.ruvival.de/ruvival-community). The final version of the literature review is only included in the Publication Series once all the feedback has been incorporated and the paper has been reviewed once again by the supervising researchers.

Beyond providing open access to research to a broader public and making it available for practitioners, we strive to directly include our readers in the process of developing our material. We hope to connect with the knowledge of a broad community and provide a deeper understanding in research fields important for sustainable rural development and in areas in need of landscape restoration.

Introduction by Ralf Otterpohl

This volume deals with energy systems and decentralised wastewater systems. While the importance of wastewater systems, and even reuse, is not so obvious – energy supply is an obvious key issue for most people who lack access to it. It has been shown in rural development projects, that it does make a lot of sense to make a combined effort of solving problems together. A qualified team will often only be available for a relatively short time span; with proper support, a lot can be accomplished by a local community, as it is mostly advice and supervision that is needed besides the hardware.

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

The most ingenious life-changing product in a region without electricity is by far a solar flashlight. I have talked to students who grew up without any light other that sunlight and a fireplace in tropical areas, where it is dark between 6 pm and 6 am all year round. In these lives, daylight time is mostly packed with the daily chores and often agricultural activities. Without light, there is no reading. In addition, without electricity there is no radio, no TV and no cell phone. The upside of this may be more conversations around the fireplace, intense family life and perhaps more space for spiritual matters. However, these advantages should be voluntary.

It is hard to conceive that millions of people still lack even simple things like a solar flashlight. On the other hand, there should be more than just that. The review of distributed renewable energy with a focus on, but not limited to Africa, shows the numerous great, and often cost-efficient, methods.

Integrated Decentralised Wastewater Treatment for Rural Areas with a Focus on Resource Recovery

One of the most stunning numbers in wastewater management is the percentage of investment costs necessary for a sewerage system relative to those necessary for wastewater treatment plants: it will typically be around 80 to 90 %, even in circumstances that are ideal for centralised systems. In other words, by far most of the investment goes into transporting wastewater from a place where reuse might be feasible to a place far away where it is mostly wasted. In peri-urban, and especially rural settings, the percentage of the investment cost needed for the sewerage system is even higher.

Sewerage systems are used for urban drainage of rainwater runoff – where actually the name sewerage comes from – however, modern alternatives for the collection of rainwater and runoff are infiltration systems recharging aquifers and sometimes the reuse of rainwater runoff, even in densely populated areas. To directly collect and store water in a natural storage system makes obviously a lot of sense, especially in water scarce areas. In rural settings, rainwater infiltration and reuse are more common and cost-efficient, but often not even considered.

A strong driving force for wastewater infrastructure is the profit margin of large and often over-dimensioned systems. As an example, many rural communities in Eastern Germany were deprived of large parts of their budgets for the construction of centralised systems, where decentralised, and sometimes on-site systems, would have been far more cost-efficient. Dynamic cost-comparison methods looking at investment and operation costs in the long run are now commonly applied and can help to identify appropriate solutions. The fact that centralised sewerage can direct wastewater away from small and vulnerable creeks to a larger river should also be considered. It is not so simple to find adequate solutions. When I was running my consultancy, we were among the rare proponents of decentralised solutions. However, there were some cases where a semi-centralised solution was better than fully decentralised ones. The need and costs of proper maintenance is often a decisive factor.

Reuse of wastewater, after or together with the treatment, is a key issue for sustainability. Hardly any of the millions of treatment plants around the world are designed for reuse of water and/or nutrients and soil conditioners. Treatment itself is only available for around 20 % of all wastewater, if we look at the worldwide perspective. If we work on rural development and water systems, we often have a choice to bring in reuse options. Unfortunately, this does not mean that it will be easily accepted. Those who are working towards a good future for all will have to present exceptionally well designed reuse systems and do it in a convincing way. It can be done, though! Counteracting water scarcity and using wastewater or sludge for reforestation can be a great door opener. Mixing excreta into wastewater and discharging this mix into the environment is still killing people, mostly small children, in the millions. Source-separation is feasible and my favourite solution is Terra Preta Sanitation (www.ruvival.de/terra-preta-sanitation-video/), but larger installations with thousands of households will be required to get this started. However, as shown in the paper, there are many other options for reuse systems available. Experience has shown that the first step for reuse is to assure that the products will be taken and used in a reliable way.

On a final note, I want to make a call for action with a simple, yet highly efficient way of wastewater treatment: bamboo-forests irrigated by wastewater. It makes sense in subtropical and tropical regions, but also in arid regions or sunny areas with moderate winters. While there is experience with willow-wastewater forests, very little has been done with the great and high-priced product of bamboo. Bamboo, contrary to willows, can take up a lot of nutrients. A bamboo-forest can be fed with conventional wastewater in an alternate way. It requires around ten times as much space as vertical constructed wetlands, but it can generate income and it can be a great part of attractive landscaping in many more rural or peri-urban settings.

Those who are interested in developing rural wastewater systems should consider working with people in the domain of distributed renewable energy systems – this can be a win-win situation and a great door opener in un- and underserved rural areas.

Inside This Volume

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

Tina Carmesin, Benedikt Buchspies, Ruth Schaldach

'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. 29)

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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 justice. However, in 2016, 14 % of the world's population still lived without electricity, mostly located in rural areas of economically poor areas. Off-grid and mini-grid systems are summarised under the term 'distributed energy systems' or 'decentralised energy systems' and provide a fast and cost-efficient method for rural electrification. Applicable technologies include solar photovoltaics, wind power, small hydropower and energy from residual biomass. Those small-scale renewable energy systems offer significant reductions in fossil fuel combustion and entailed emissions of greenhouse gases. This paper reviews distributed renewable energy systems and concentrates on energy services for electricity generation in rural Africa. Whereas political uncertainty and a lack of access to investment capital are major barriers for implementing these services, the systems' contribution to energy security, their flexibility, affordability, modularity and environmental sustainability are driving forces for their expansion. Investment and payback times are often very much lower than those of large-scale centralised systems with their highly expensive and vulnerable networks.

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*

Introduction

Access to energy 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 many 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 increasing prosperity, rapid economic and population growth. 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 have 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. 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 the lack of capital 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, therefore, presented. Finally, opportunities and obstacles for distributed energy systems in Africa are discussed.

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. Even in serviced areas electricity supply is frequently interrupted for extended time periods.

Africa is the continent with the lowest electrification rate. As presented in Figure 1 (see p. 10), 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, cited in Quitzow et al. 2016).

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 an important factor for human development. It comprises education opportunities and health, but also affects agricultural or economic activities, as well as access to an improved water supply and sanitation. At the same time, Africa will be one of the continents most affected by climate change and many countries will probably experience exacerbated water scarcity, health and food security risks (Quitzow et al. 2016).

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). In addition, adequate access to affordable, reliable, high quality, safe and environmentally sound energy services to meet basic needs is missing. 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). In most countries, power is still generated in large, centralised power plants using coal, natural gas, nuclear power, hydropower or solar energy as the energy source (IEA 2017a).

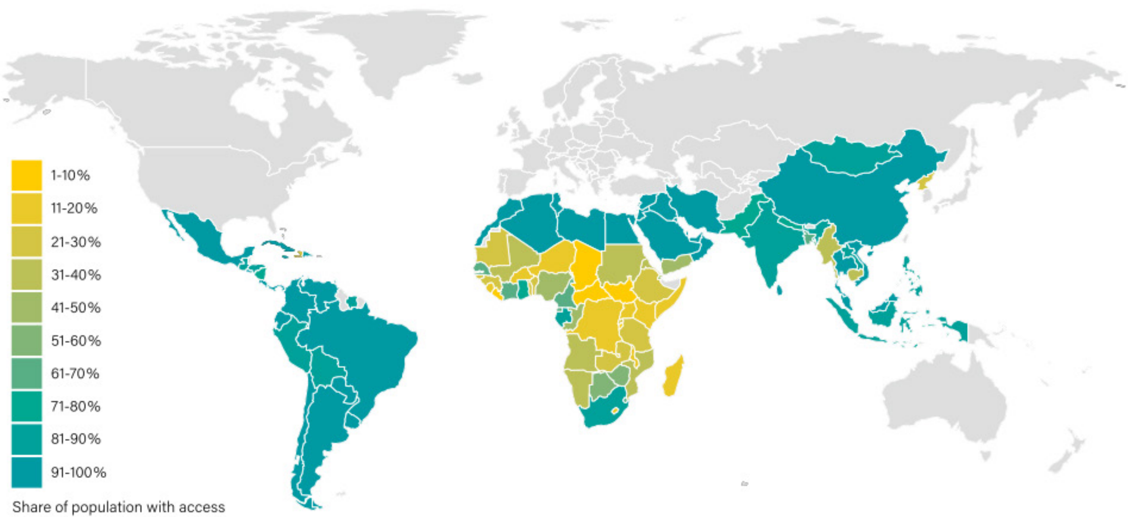

Figure 1 Electricity Access in Developing Countries, 2014 (REN21 2017, p. 98)

However, decentralised generation can also be connected to the transmission network at low voltage (e.g. solar photovoltaic (PV) units) (IEA 2017a). 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 are not connected to the transmission network, but have an independent distribution network (IEA 2017a; REN21 2014). They vary in size and 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 – 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 a 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 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 (IEA 2017a; REN21 2017). 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

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

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 (Victor et al. 2014). Worldwide, electricity and heat production were responsible for a share of 42 % of the global greenhouse gas emissions in 2016 (IEA 2018a). 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). 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 emit nitrogen and sulphur oxides, as well as of other pollutants with adverse health and environmental effects. 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 (Bruckner et al. 2014). More specifically, these concerns arise regarding accident prevention, but also comprise normal operation (German Environment Agency 2015). 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). In addition, there is the possibility of military use of radioactive material. Each of the abovementioned concerns pose a risk for humans and the environment (German Environment Agency 2015).

The following systems for renewable electricity generation will be described: small-scale solar PV, wind turbines, small-hydro technologies and electricity from biomass. As the presented technologies differ widely in their generation capacity, their specific application is diverse. Some systems may be used to provide lighting and mobile phone charging, which can significantly change people's lives. 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 2017b). In the cell, which consists of semiconducting materials, 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 PV cell's efficiency, 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 you can choose from a rich variety of sizes. 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 2017b).

Pico-PV systems comprise the smallest distributed solar PV systems. These systems usually consist of a solar panel, a battery, one or several 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 26 million pico-PV systems were sold worldwide. This represents 87 % of all off-grid solar product sales (Dalberg Advisors, Lighting Global & Global Off-Grid Lighting Association 2018, p. 57). However, it needs to be kept in mind that pico-PV systems offer very limited individual electricity generating capacity.

Solar Home Systems (SHS) enable the provision of electricity for basic requirements in regard to lighting and communication technologies in households (Sauer, Rau & Kaltschmitt 2007). This includes to run a radio and television, as well as information and communication technologies and a refrigerator (Alliance for Rural Electrification 2011). 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), telecommunication, navigational aids, health clinics, educational facilities and community centres (REN21 2017).

Sales of SHS are constantly growing. In 2016 793,000 systems were sold worldwide (Dalberg Advisors, Lighting Global & Global Off-Grid Lighting Association 2018, p. 61). 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-powered 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). The stored water can be used for irrigation or other purposes.

Figure 3 A Solar-Powered Pump System Is Combined with Drip Irrigation at Faylar Village in Senegal

Initial costs for solar-powered 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. Therefore, solar-powered pumps offer a cost-effective alternative to grid- or diesel-based pumps, for example for irrigation (Omer & Omer 2007). Since operational costs of PV-powered pumps are negligible, there is the risk of excessive water withdrawal associated with this technological turn (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 2017a). 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 so that they are 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 2017b).

In recent years, off-grid solar energy (pico-solar and SHS of less than 100 W) has been one of the fastest growing industries in the provision of electricity access. Whereas in 2010 about 900,000 off-grid solar systems were sold worldwide, sales continued to increase to about 30 million in 2016 (Dalberg Advisors, Lighting Global & Global Off-Grid Lighting Association 2018, p. 57). In 2016 sales were the highest in India, followed by Eastern African countries. Kenya, Ethiopia, Uganda and Tanzania accounted for an estimated 70 % of sales of pico-PV and SHS in sub-Saharan Africa (Global Off-Grid Lighting Association & Lighting Global 2017, p. 18).

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 generates electricity (EIA 2017c). Small-scale wind turbines are in most cases coupled with a battery and a battery charge regulator and provide electricity for farms, homes and small businesses, water pumping and telecommunication (Kaltschmitt, Skiba & Wiese 2007).

Several definitions of small wind turbines exist. Technically, the standard IEC 61400-2 defines a rotor swept area of less than 200 m², generating at a voltage below 1,000 V AC or 1,500 V DC (IEC 2013, p. 11). A rotor swept area of 200 m² 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, p. 335; WWEA 2017, p. 10) use an upper nominal capacity limit of 100 kW in their definitions. 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 1 kW and 10 kW. In case of rural household supply, even wind turbines below a diameter of 2 m and with a 1 kW output can be used (Alliance for Rural Electrification 2011, p. 18).

Small wind energy systems cover fast converters with 2 to 3 rotor blades as well as slow converters with numerous rotor blades. Additionally converters can be equipped with vertical axes, for example a Savonius type or H rotor (Kaltschmitt, Skiba & Wiese 2007, p. 335). However, systems with a horizontal axis dominate the market (WWEA 2017, p. 7).

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 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. Smooth, rounded hilltops, open plains or water and mountain gaps that funnel wind are therefore good sites for installation (EIA 2017d).

Small-scale wind systems are spread around the world. China, reaching 415 MW in 2015, accounts for 44 % of the global installed capacity. Developing countries only offer limited amounts of small-scale wind power capacity (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 rivers offer the best opportunities for power generation capacity (Alliance for Rural Electrification 2011).

The classification small-scale hydroelectric power is used frequently without further definition. Similar to the discourse on defining small-scale wind power systems (see p. 15), 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),
- up to 300 kW in Switzerland (Jorde & Kaltschmitt 2007b, p. 354).

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

- small hydropower plants (< 10 MW),
- mini hydropower plants (< 1 MW),
- micro hydropower plants (< 100 kW),
- pico hydropower plants (< 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) 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).

Besides the choice of the system, the plant's layout and surroundings are a major concern during 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 around 16 % of global electricity production in 2018 (IEA 2018b). 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 or animals and resulting residues, by-products and waste and dead, but not yet fossil, organic materials (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 electricity generation 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), do not list bioenergy technologies for electricity supply in rural areas. Otterpohl (2015) emphasises the environmental impacts and suggests the usage of woodgas stoves and woodgas units for cooking, especially as they offer further synergistic benefits if implemented with a Terra Preta sanitation system. Nevertheless, energy from biomass is primarily used and recommended for cooking and heating purposes in rural areas, but nor for electricity generation.

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.

Renewable Hybrid Systems

In hybrid systems, different power generators complement each other in terms of temporal availability. This ensures a steady energy supply, as the energy supply of the previously characterised power systems are influenced by fluctuations due to varying weather, availability of sunlight or changing seasons. Therefore, hybrid systems are used, if a reliable energy supply independent of weather conditions or season is required (Sauer, Rau & Kaltschmitt 2007).

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

As shown in this chapter, there is comprehensive technological expertise for rural electrification. Depending on local conditions and user preferences, different technologies can be used. 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 (e.g. monocrystalline cells, multi-crystalline cells) (Kaltschmitt, Schröder & Schneider 2007). A more detailed analysis of these severe effects is provided by Kaltschmitt, Schröder & Schneider (2007). 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 ground use (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 2017e). 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 the risk of hitting birds (Kaltschmitt, Skiba & Wiese 2007). In addition, the EIA (2017e) 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. 16), 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 from 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 of biodiversity, interrupted migration of fish, change in the composition of species (including mammals, birds and amphibians due to changed food availabilities), 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) 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 between land usage for food or energy crops and connected water usage. 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 the German Advisory Council on Global Change (2009b). Energy crop cultivation may displace existing food or feed production or grazing space, with the consequence that the displaced land-use 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). Otterpohl (2015) highlights the impact of bioenergy production on soil degradation. Mandelli et al. (2016) see a sustainable use of bioenergy for power generation as quite difficult in rural areas, due to 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 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 impacts. 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 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 trade-offs. 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, undernourishment 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 between humans and the environment (Howarth & Monasterolo 2016). 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. Thus, governments, the private sector, communities, the academic world and other stakeholders are allowed 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.

Although the entire African continent makes up about 1 % of the world's CO_2 emissions (Millennium Resource Strategies Limited 2015, p. 4), 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, such as improved air quality, biodiversity conservation or mitigation of water-related risks (Somanathan et al. 2014). Also deforestation and environmental degradation can be reduced (German Advisory Council on Global Change 2009b).

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, it shows that the share of investment provided for energy access and distributed renewable energy is comparatively small. While public international finance for climate change and clean energy systems covered in total about US$ 14.1 billion from 2003 until 2015, only 3 % were allocated to distributed renewable energy systems (Rai, Best & Soanes 2016, p. 7).

Therefore, 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, the African Development Bank awarded US$ 1 million to the Republic of Niger and US$ 840,000 to Rwanda to foster the development of mini-grids (Cunha 2016).

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. More so, there is an increasing trend of international private equity targeting the renewable energy sector in Africa, mainly regarding wind and solar systems (Quitzow et al. 2016).

An emerging innovation in off-grid technologies creates economic and entrepreneurship opportunities for African companies. 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 (REN21 2017).

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 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, p. 107). However, criticism about their business model exists. Notably, in an article published in Bloomberg Businessweek, Faris (2015) accuses M-KOPA SOLAR of making profit from poor Africans. Initially M-KOPA SOLAR sells SHS, but tries to sell more products on instalments 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 US$ 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 (IEA 2017a). In 2017 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 (Theron 2017).

For PAYG energy services, mainly solar systems are used. The most popular system 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 a low level 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 US$ 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 (BloombergNEF 2017, cited in 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,
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, however, more programme developments in regard to distributed renewable energy are in motion.

Strategies and Policies

In order to support the deployment of distributed renewable 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 Cape Verde that promotes renewables (Quitzow et al. 2016). Another example is the Nigerian Electricity Regulatory Commission, that passed a regulation specifically about permission and operation procedures of mini-grids (Nigerian Electricity Regulatory Commission 2016).

Strategy plans are implemented in order to move away from the strategy of grid expansion for rural electrification. Recently, policies were implemented by several countries for a decentralised approach of rural electrification based on renewable energy sources (Quitzow et al. 2016). For instance, Uganda adopted the Rural Electrification Strategy and Plan of 2013 – 2022 that includes support for community-based[1] mini-grids and solar PV systems (Ministry of Energy and Mineral Development Uganda 2013). Kenya implemented a Feed-in-Tariff in 2012 that includes solar mini-grid systems (Ministry of Energy Kenya 2012). Sierra Leone exempted all VAT and import duties from SHS (Wheeldon 2016, cited in REN21 2017, p. 108).

[1] 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.'

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

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 opportunities and constraints to implement those systems and their role in rural electrification.

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, which have no access to energy services (Sovacool & Ryan 2016, p. 107). 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) make construction manuals for several machines available free of charge. Users are enabled to gain this information and put it into practice. An example is Libre Solar, an open hardware project currently with a 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[2]. However, open source knowledge is not limited to these examples, there are many fields on open source knowledge.

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),

[2] https://collectiveopensourcehardware.github.io

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 lighting, 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 (Yadoo & Cruickshank 2012). 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 (Quitzow et al. 2016). Compared to fossil energy technologies, renewable-based technologies provide more employment opportunities due to higher labour intensity (Jacob, Quitzow & Bär 2015), 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 (Quitzow et al. 2016), like: extended opening hours enabled by lighting, as shown in Figure 4, or the diverse income generation possibilities of a business owner in Uganda explained in Figure 5 (see p. 27).

Figure 4 Lights Are Used to Extend Opening Hours of a Shop

[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 the 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 Diecker, Wheeldon & Scott (2016), 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 reduce competitiveness of alternatives. 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 derisking 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. 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. 24), several countries implemented policies and strategies to support rural electrification.

Technical Barriers

Even though Rachel Kyte, the Chief Executive Officer of SEforALL and Special Representative of the UN Secretary-General for SEforALL, says that ‘policy and finance have to catch up with technology’ (Brent 2016), renewable energy deployment in Africa still 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 name 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.

Modularity and Flexibility

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). 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 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 a distributed energy development (see p. 22), customers and companies may lack access to investment capital. Quitzow et al. (2016) name cost recovery as a particular challenge for rural electrification efforts as the costs for electricity supply in rural areas are usually higher than the national average. 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 in setting cost-covering tariffs in addition to an 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 a main grid extension unfeasible. Areas that are not yet electrified have a very low demand and load factors, making small-scale generation 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, consequently the availability of finance 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 a cost-effective and quick way to provide basic level electricity access (such as lighting 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 a grid expansion (IRENA 2016; REN21 2017). Also the IEA (2017a) sees 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, as well as from industrial or commercial facilities (IEA 2017a).

If the option of connection is available, the IEA (2017a) states that grid extension enables the lowest costs to supply households with electricity: levelled cost of electricity through mini-grids is higher than a centralised transmission and distribution network system. In contrast to that, REN21 (2014) report 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 a 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 costs are compensated by the lower upfront costs 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. The use of currently available energy efficiency measures could cause the supply of universal access to modern energy services by using 50 – 85 % less energy than prevailing estimates state is required (REN21 2017, p. 102). Pico-PV systems are an example for decreasing 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 driving 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 fluctuations in 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 unaffordable 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. 18).

Distributed renewable energy systems offer a significant potential for the electrification of rural households. Among other advantages this development can 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 driving forces for their expansion.

Conclusion

Distributed renewable energy systems provide unprecedented chances 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 finances 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 (p. 10) Electricity Access in Developing Countries
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/> - Copyright notice: You are welcome to use the information contained in this report free-of-charge. We ask that you: 1) Include the following citation REN21, <year of publication> <Name of publication> (Paris: REN21 Secretariat) 2) Send a copy of the final work to: secretariat@ren21.net.

Figure 2 (p. 13) People Using Light and Charging a Mobile Phone through SHS
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 (p. 14) A Solar-powered Pump System is Combined with Drip Irrigation at Faylar Village in Senegal
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 (p. 26) Lights are Used to Extend Opening Hours of a Shop
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 (p. 27) The 500 W Solar System Powers a Home, a Public Broadcasting System, a Barbershop and a Video Hall in a Rural Village in Uganda
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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Integrated Decentralised Wastewater Treatment for Rural Areas with a Focus on Resource Recovery

Usama Khalid and Carla Orozco Garcia

'Adequately managed decentralized wastewater systems are a cost-effective and long-term option for meeting public health and water quality goals, particularly in less densely populated areas.'

United States Environmental Protection Agency (US EPA 1997, p. i)

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Abstract

The most appropriate and sustainable solution for wastewater management in any setting is economically, environmentally, and technically sound, as well as socially acceptable for the specific community. Centralised wastewater collection and treatment systems are criticised for being resource intensive and technically too complex, especially for sparsely populated regions with dispersed settlements. Alternatively, the approach of decentralised wastewater treatment appears as a sustainable solution to address these issues related to rural wastewater management. This paper presents a review of the advantages and limitations of various centralised and decentralised approaches to wastewater treatment and management in rural settings. A sustainable solution to wastewater management in rural areas based on the concept of ecological sanitation, with focus on water and nutrients recovery is presented. Based on research and case studies, the potential of an integrated decentralised wastewater system for rural areas is examined from a technical, economic and environmental viewpoint.

Keywords: *wastewater management, resource recovery, decentralised wastewater treatment, source separation, sustainability, centralised vs decentralised systems, rural areas, circular economy*

Introduction

In spite of the continuous fast urbanisation, around half of the total global population still lives in rural areas. In the European Union (EU), around 91.4 % of the settlements in Central and Eastern European countries have inhabitants under 2,000, which translates to 20 % of the total Central and Eastern European population (Vrhovšek 2007, p. 8). According to the Eurostat Yearbook (EU 2017, p. 252), around 28 % of the EU-28 total population in 2015 lived in rural settings. Numerous regions of the world demonstrate a dominantly rural or peri-urban (settlements in the vicinity of extensive urban regions) character. 'United Nations Sustainable Development Goals' objective 6 anticipates to accomplish by 2030, access to safe and sustainable sanitation and hygiene for all, and reducing the percentage of untreated wastewater by half while considerably expanding and promoting recycling and safe reuse in developed and developing countries (UN-Water 2016). Despite the efforts to improve the wastewater treatment and management around the globe, around 4.5 billion people still lack access to safe and adequately managed sanitation services (UNICEF & WHO 2017, p. 29). As can be seen in Figure 1, most of these people are found in sub-Saharan Africa and South Asia. According to WWAP (2017, p. 2), globally around 80 % of wastewater is returned to the ecosystem without proper treatment or reuse. The absence of adequate wastewater treatment is usually significantly higher in rural communities and small settlements with a population less than 10,000 Population Equivalents (PE) (WHO & UN-Water 2014).

The term wastewater is defined as a combination of liquid waste from domestic residences, commercial and institutional settings, industries, agriculture, farming practices, aquaculture, storm water and runoff from urban areas (eds Corcoran et al. 2010). Domestic wastewater consists of blackwater (faecal sludge, urine, flushing water and anal cleansing water or materials) and greywater (water used for washing food, dishes, clothes and wastewater from bathing and sinks).

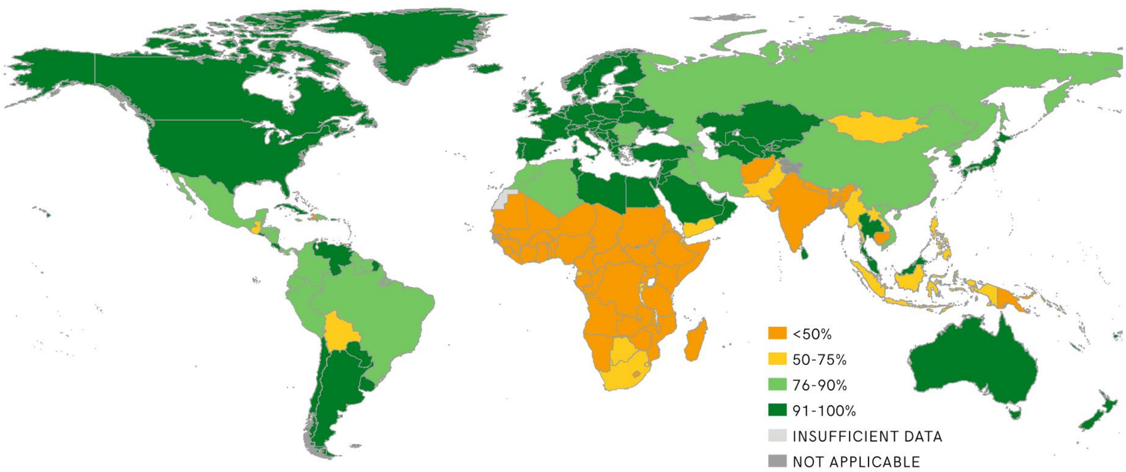

Figure 1 Proportion of National Population Using at least Basic Sanitation Services (UNICEF & WHO 2017, p. 4)

Blackwater is further divided into brownwater (mixture of faeces and flushing water, with or without anal cleansing water or materials) and yellowwater (urine diluted with flushing water) (Tilley et al. 2014). Domestic wastewater approximately contains 99.9 % water and only 0.1 % is a mixture of dissolved and suspended solids, organic and inorganic compounds, pathogens and other microorganisms and nutrients, including phosphorus and nitrogen (Sperling 2007, p. 28). According to Sperling (2007, p. 57) domestic sewage wastewater composition can range from 500 – 900 mg of Total Dissolved Solids (TDS), 200 – 450 mg of Total Suspended Solids (TSS), 250 – 400 mg of Biological Oxygen Demand (BOD), 35 – 60 mg of nitrogen, and 4 – 15 mg of phosphorus per litre.

In rural communities, sanitation practices involve serious health, economic and social issues, that highlight the dire need to develop technologies which suit the local realities and are at the same time cost-effective, more efficient and easy to maintain (Kadlec & Knight, Philippi & Sezerino, cited in Lutterbeck et al. 2017). Rural communities mainly depend on on-site wastewater treatment systems with little or no access to public sewers (Wu et al. 2011). Several options exist for on-site wastewater treatment technologies including septic tanks, lagoons, drain-field systems, aerobic biological treatment units, constructed wetlands (CW) and membrane biological reactors (MBR) (Nakajima, Fujimura & Inamori 1999). These advanced decentralised treatment systems make sustainable sanitation and safe water reuse applications possible, if not yet widely practised (Rodale Institute 2013).

The affordability and appropriateness of the technology plays a major role in the selection of the most suitable decentralised wastewater treatment system for a given community (Wu et al. 2011). In any situation, the most appropriate solution for wastewater management is the one that is economically, environmentally and technically sound, and socially acceptable for the community (Capodaglio 2017). To accomplish the goals of adequate wastewater treatment and sanitation, the community should evaluate all the treatment options available. This requires a lot of diligence for the community and reliable information from outside sources. Eco-innovation can be the solution to improving the sustainability of wastewater systems by reducing their environmental impact and by making them economically, environmentally and socially efficient (Capodaglio 2017).

Decentralised Wastewater Treatment vs Centralised Wastewater Treatment

In wastewater treatment science, the political debate of centralised vs decentralised wastewater systems is reflected by the scientific discourse and research strings. This global discussion has highlighted various economic, technological, environmental and social barriers or advantages in both systems, making it difficult to prioritise one over the other. Subsequently, to consider the particular conditions of the site and settling on a case-by-case premise is a common approach. Rural communities in the developing and the developed world face often the same question, that is, to prefer centralised or decentralised systems for effective wastewater management (Libralato, Volpi Ghirardini & Avezzù 2012).

Centralised Wastewater Treatment Systems

A centralised wastewater treatment system appears as a more feasible solution for densely populated regions, already connected to the sewerage collection and transport system (Hophmayer-Tokich 2006; Libralato, Volpi Ghirardini & Avezzù 2012). Around 80 – 90 % of the investment costs of centralised systems are subjected to the collection system (Bakir 2001, p. 325). In this way, the cost of the overall sewerage system in centralised systems can be distributed over a large population (Jones et al. 2001). A centralised system is characterised by the collection and treatment of wastewater by a combination of centralised sewerage and a centralised treatment plant, treating the wastewater and disposing it under controlled conditions. These systems, by definition, serve large and densely populated areas with multiple dwellings and households. They require high investment costs, implementation of high-tech solutions, and therefore, highly trained labour and a complex system operation. One of the major advantages of centralised wastewater systems is uniformity, fulfilling the water demand, while meeting quality standards for a large area (Capodaglio 2017).

Decentralised Wastewater Treatment Systems

Decentralised wastewater management systems are designed for a relatively low volumetric flow of wastewater from houses or dwellings that are located comparatively close to each other (less than 3 – 5 km), and are not connected to a central sewer system and a centralised wastewater treatment plant (WWTP). Decentralised wastewater treatment systems, when properly designed, constructed, maintained and operated, are found to be cost competitive with centralised wastewater treatment systems, taking into consideration the costs associated with the sewerage collection system (Ho & Anda 2004; Tchobanoglous 2002). Decentralisation provides a solution based on a holistic approach, it reaps additional benefits by reducing the wastewater volume at source, thereby reducing the treatment costs and increasing the recycling or reuse of the resources in the wastewater. Local reuse of the components recovered from wastewater can help to close the resource loops, therefore supporting the basic principles of a circular economy[1] (Capodaglio 2017).

According to Orth (2007), decentralised systems mainly fall into three categories:

- simple sanitation systems minimising the sanitary issues through retention of faecal matter and discharge of the effluent (for example pit latrines, septic tanks and pour-flush toilets),
- small-scale mechanical-biological treatment plants offering a natural-like treatment (for example septic tanks, constructed wetlands and lagoons),

[1] 'A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations' (Kirchherr, Reike and Hekkert 2017, pp. 224-5).

- recycling systems maximising the potential of resource reuse and recycling (such as ecological sanitation).

Different types of wastewater treatment systems ranging from a conventional large-scale centralised system to an extremely local and individualistic decentralised treatment system are shown in Figure 2 (Libralato, Volpi Ghirardini & Avezzù 2012).

Decentralised wastewater systems have several advantages over centralised wastewater systems and can be summarised in terms of cost-efficiency (capital and operational costs), potential for resource recycling, improved water quality and availability, efficient land and energy usage, growth responsive and increased stakeholder involvement.

As discussed by Brown, Jackson & Khalifé (2010), decentralised systems have the advantage of flexibility and can be built just in time to meet local demands. By taking advantage of state of the art cost-effective technology, decentralised systems usually involve a small initial investment for a community, compared to large-scale centralised systems. Decentralised systems can allow communities to delay or avoid costly infrastructure capacity upgrades involved in larger systems. A sustainable and financially sound solution for wastewater management in rural settings could be to switch from conventional systems to local cluster-based on-site treatment systems (eds Novotny & Brown 2007).

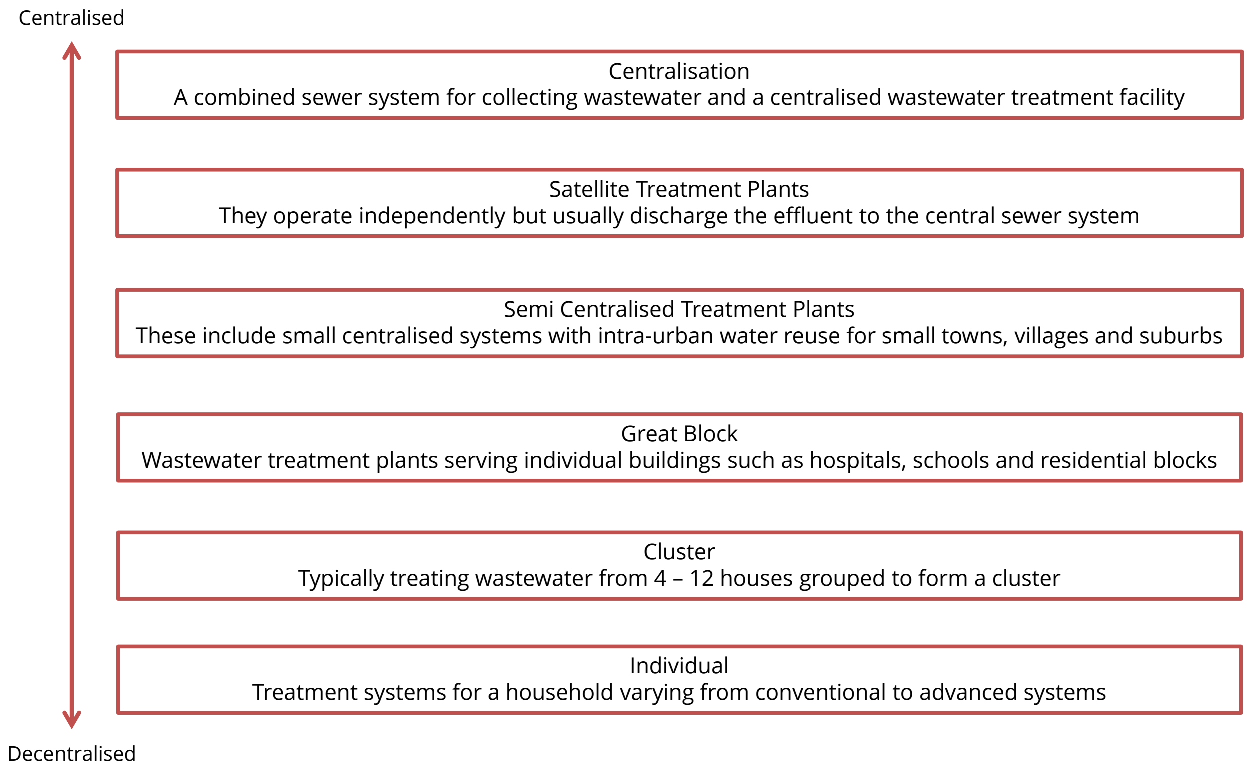

Figure 2 Different Types of Wastewater Treatment Systems, Based on Libralato, Volpi Ghirardini & Avezzù (2012)

According to Maurer, Rothenberger & Larsen (2005), after every 50 – 60 years, a centralised collection system or some parts of it require complete renovation, apart from mandatory periodic maintenance, therefore leading to increased maintenance costs and causing disruptions to public utilities. The operation and maintenance cost per unit of treated organic load associated with a decentralised system is becoming comparable to that of a centralised system (Fane & Fane 2005).

Decentralised systems incorporate small and relatively simple technologies that are easy to operate and cost-effective. The experts and finances required to operate, maintain and replace the system is usually low. Additionally, decentralised systems treat wastewater close to the source and generally include passive treatment, such as soil dispersal, leading to considerable savings in energy costs (US EPA 2015).

According to Capodaglio (2017), decentralised wastewater treatment plants focused on onsite treatment can lead to higher environmental sustainability by facilitating the reuse of treated wastewater for various purposes, as well as resource recovery. Decentralised systems can lead to the reduction of negative environmental effects, while prioritising public health and increasing the ultimate reuse and recycling of valuable resources in wastewater, depending on the technical options, community type and local settings (Ibrahim & Ali 2016). Decentralised systems can be designed to separate the contaminants at source, facilitating the treatment and potential resource reuse and energy savings (Brown, Jackson & Khalifé 2010; Tchobanoglous & Burton 1991).

Decentralised wastewater systems efficiently and effectively treat domestic sewage and protect local water quality and local water supplies. The wastewater, after being treated by decentralised systems, can recharge the groundwater, as it seeps into the underlying ground, therefore benefitting the local watershed (US EPA 2015). However, proper measures need to be taken in order to avoid groundwater pollution (Hophmayer-Tokich 2006). Modern decentralised treatment systems have been proven to achieve the same level of reliable treatment compared to other conventional wastewater treatment alternatives, while being financially and technically sustainable (Ghimpusan et al. 2016). Capodaglio (2017) argues that centralised systems are more prone to destruction by natural disasters, whereas decentralised systems appear as a more resilient option for wastewater management with lower vulnerability to climate-induced extreme events, power outages, and sabotage episodes.

Decentralised systems also utilise the land efficiently and minimise the issues related to local site conditions. They are carefully designed for a specific community, taking into consideration the local soil and land properties, therefore avoiding the problems with groundwater tables, bedrock formations and soil infiltration rates (Massoud, Tarhini & Nasr 2009). Decentralised systems also take advantage of gravity flow rather than using energy to pump the wastewater, leading to reduced energy consumption (Jones et al. 2001).

Decentralised systems offer more flexibility and can handle the problems associated with suburban areas and rural centres (re)-development and population growth more effectively (Wilderer and Schreff, Tchobanoglous, Tchobanoglous et al, Ho and Anda, Ho, Lamichhane, Weber et al, Brown et al, cited in Libralato, Volpi Ghirardini & Avezzù 2012). They can be designed to meet specific growth goals, considering the expected growth pattern of the community. They tend to have small environmental footprints and can provide opportunities to build green spaces in the region (US EPA 2015).

According to a report published by US EPA (2015), decentralised systems could lead to greater economic opportunity for local stakeholders such as installers, inspectors and designers. Local experts, with better understanding of the culture and values, can effectively help in designing an efficient system. Decentralised management of wastewater can lead to greater stakeholder involvement, as they provide more opportunities for awareness, involvement and participation of local users than centralised systems, which leads to increased acceptance of their objectives and advantages (Capodaglio 2017).

Considering the advantages of decentralised wastewater treatments, the decentralisation approach constitutes as a sensible and sustainable way to address the wastewater issues in sparsely located and low income regions (Capodaglio 2017).

Rural Decentralised Wastewater Treatment Technologies

In decentralised wastewater treatment, there are numerous approaches for the collection, treatment and dispersal/reuse of wastewater for clusters of homes or businesses, individual dwellings and entire communities. Treatment options range from simple on-site or septic systems, providing passive treatment with the effluent being dispersed to the soil, to complex systems utilising mechanical or biological processes with high treatment efficiency, dispersing the treated effluent to the soil or to water bodies (US EPA 2015). They usually treat the wastewater near the point where it is generated (Massoud, Tarhini & Nasr 2009). The typical systems are discussed in the following section.

Primary Wastewater Treatment Systems

Primary treatment methods are inexpensive and simple to operate and maintain but the efficiency of the system to remove phosphorus and nitrate compounds and pathogenic organisms is generally low (Massoud, Tarhini & Nasr 2009). These systems can be used prior to further treatment and disposal. Based on the literature review, the advantages and limitations of typical primary treatment methods are summarised in Table 1 (see p. 46). These methods are discussed as follows.

Septic Tanks

The conventional septic tank constitutes a simple, cost-effective and low maintenance treatment option for areas with low population density and favourable soils. The treatment system consists of a septic tank followed by a drain field, alternatively known as a leach field. The wastewater from the house enters the septic tank where it is anaerobically degraded, the solid fraction is retained, while the liquid fraction exits the tank by means of an outlet pipe (Joubert et al. 2005).

Table 1 Advantages and Limitations of Primary Treatment Methods (Joubert et al. 2005; Washington State Department of Health 2004; Wendland et al. 2007; Zhang 2012)

Primary Treatment Methods	Advantages	Limitations
Septic Tank	• Simple in design • Cost-effective • Low maintenance • Low energy requirements • Removes most of the settleable solids	• Removes only 30 – 35 % of BOD and 25 – 35 % Chemical Oxygen Demand (COD) (Sperling 2007, p. 221) • Not considered a nitrogen reducing treatment option • Odour problems, if not properly maintained • Pretreatment required
Cesspools	• Simple in design • Low maintenance and capital costs • Energy independent systems	• High risk to water quality and public health • Discharge of untreated water to the subsurface • Requires periodic replacements and upgrades
Holding Tanks	• Flexible operation • Temporary solution for difficult sites	• Energy intensive because of periodic pumping • Not a permanent solution • No treatment provided
Ecological Sanitation	• Cost-effective • Suitable for low income regions • Low maintenance • Low energy requirement • Resource recovery and reuse	• May require a lifestyle adjustment • Odour problems, if not properly maintained

Cesspools

Cesspools are old fashioned systems that retain the solid portion of the wastewater in the interior, while the liquid fraction seeps into the surrounding soil. Cesspools typically comprise of a covered pit with walls made of loose, dry fitted rock with a concrete or steel leaking chamber. The use of cesspools can lead to deterioration of the local water quality and hazards to public health due to the possible discharge of untreated and hazardous wastewater to the surrounding soil and nearby waterbodies (Joubert et al. 2005).

Holding Tanks

As a last resort, a holding tank, alternatively known as a tight tank, can be used, if allowed by local bodies, on extremely difficult sites. It is similar to a septic tank but without an outlet to a drain field, which has to be regularly pumped or drained when full. Usually regulatory programmes prohibit the use of holding tanks; they may only be used as a brief arrangement while a repair for a site is finished, or as a standalone treatment system for complex sites, where advanced systems are to a great degree impractical or unfeasible (Joubert et al. 2005).

Ecological Sanitation

Ecological sanitation is based on the concept of source separation of domestic wastewater streams into grey-, brown- and yellowwater, with appropriate treatment of each stream in decentralised systems to facilitate the reuse of water and recycling of nutrients (Wendland et al. 2007). The greywater component, comprised mainly of water from sinks, showers, kitchen and washing machines, corresponds to nearly 65 % of the total domestic wastewater (Tilley et al. 2014, p. 11). Having a very low concentration of pathogens, it can be effectively treated via systems such as constructed wetlands and then reused as a valuable water resource for non-potable purposes (Behrendt et al. 2006). Brownwater is rich in organic material as well as nutrients like nitrogen, phosphorus and potassium; and it can be applied on the field for non-food crops to enhance soil fertility. Before applying it to the soil, it has to be treated to assure sanitisation by processes such as vermicomposting (Bettendorf, Stoeckl & Otterpohl 2014). The yellowwater component is rich in nutrients necessary for plant growth and can be used as a direct fertiliser supporting non-food crop production; moreover, it can replace the need for additional treatment steps required to remove phosphorus from wastewater in conventional wastewater treatment systems (WHO 2006).

Primary treatment options do not constitute a standalone option for adequate wastewater treatment. They must be integrated with other treatment options to ensure the effective removal of harmful and hazardous substances present in the wastewater. The choice of the best primary treatment option is, however, subjective to the given site conditions and resources available.

Secondary Wastewater Treatment Systems

Various secondary treatment methods exist for decentralised wastewater treatment, having numerous advantages and limitations. Integrated decentralised treatment systems are different from conventional systems in terms of having an additional treatment unit, which further treats the wastewater from primary treatment units, before it is finally discharged to the drain field; the additional treatment step enables the system to achieve high and consistent efficiency (Joubert et al. 2005). Based on the literature review, the advantages and limitations of main secondary treatment methods are summarised in Table 2 (see p. 48). These methods are discussed as follows.

Waste Stabilisation Ponds

Waste stabilisation ponds include simple systems such as aerobic, anaerobic and facultative ponds that combine aerobic and anaerobic processes. The major advantages of waste stabilisation ponds are their simplicity and a long retention time, constituting an effective treatment option for the reduction of pathogen levels. Additional economic benefits can be reaped as they provide a good environment in ponds to support aquatic life such as tilapia fish. A high algae concentration in the effluent from ponds makes it suitable for irrigation purposes. One of the major limitations of waste stabilisation ponds is their large land area requirements (Parkinson & Tayler 2003).

Table 2 Advantages and Limitations of Secondary Treatment Options (Capodaglio 2017; Joubert et al. 2005; Parkinson & Tayler 2003; Wendland & Albold 2010)

Secondary Treatment Options	Advantages	Limitations
Waste Stabilisation Ponds	• Removal of more than 75 % COD (Wendland & Albold 2010, p. 13) • Low capital costs and simple operation • Energy is required only for pumping • Simple operation and maintenance • No electromechanical machinery • Partial removal of nutrients	• High evaporation rate • Quality of discharge varies according to season • Space demand can be very high • Predictable nuisances may include odours, insects, and pests
Media Filters	• Single pass filters are efficient in pathogen removal while recirculating media filters can also lead to nitrogen reduction • Removal of >75 % COD (Wendland & Albold 2010, p. 13) • High quality effluent especially for BOD and TSS • No chemicals required	• High installation and operational costs • High energy consumption • High costs associated with filter media • Efficiency may be reduced over time
Membrane Biological Reactors	• Effective in removal of organic matter; some types of micro pollutants and nutrients, if operated properly • Medium operational costs per unit of organic pollutant removed • The treated water meets the requirements for water to be reused for non-drinking purposes • Low space requirement	• High energy demand • High capital and construction costs • Complex systems • Skilled labour required • Nuisances including odours, noise pollution, and traffic problems • Extremely high cost of aeration and filter media
Anaerobic Digestion	• Effective in removing organic matter • Low energy demand • Effluent and excess sludge high in nutrients • Energy recovery as biogas • Low costs associated with physical infrastructure • Personnel do not need complex skilled training	• Little disinfection performed • Effluent usually needs postprocessing • Nuisances including odours, noise pollution, and traffic problems
Constructed Wetlands	• Effective removal of organic matter and to some extent, nutrients • Integration with existing ecosystems is possible and feasible • Returns water to the natural cycle • Nutrients are recycled into biomass • Very low energy requirements and emissions • Cost-effective and robust • Simple to construct and operate	• Possible water losses due to high evaporation in arid countries • Requirement to remove and dispose biomass periodically • Nuisances including odours, insects, and pests • Main limitation is the surface area needed for construction

Secondary Treatment Options	Advantages	Limitations
Terra Preta Sanitation (TPS)	• Conversion of organic waste and faeces or excreta into highly fertile black soil • Allows carbon sequestration • Stable process • High pathogen reduction • Cost-effective • Nutrients are recycled as fertilisers • Soil enhancement	• May require a life style adjustment • Odour problems if not properly maintained • Requires input of charcoal, lactic acid bacteria, woodchips and external carbon source if only faeces or excreta are treated (e.g. kitchen waste or molasses)

Media Filters

Media filters are composed of a lined or water-tight structure containing media. They utilise different physical and biological processes to degrade the wastewater and remove the contaminants. The effluent from a septic tank is pumped and introduced from the top of the filter over the media surface. The media provides the necessary surface area and the required retention time for the wastewater to be degraded (Joubert et al. 2005).

The most conventional type of media filter bed is a single pass sand filter; it has been known for long as the industry standard. Single pass sand filters effectively remove the pathogens from the wastewater, but they are not considered a nitrogen reduction option. While in recirculating filters, the effluent from the media is recirculated between the tank and the filter several times before finally discharging it to the nearby drain field. In recent years, non-absorbent granular media such as sand has been replaced by alternative media like peat and textile to achieve a more efficient wastewater treatment (Joubert et al. 2005).

Membrane Biological Reactors

MBRs involve biological degradation of wastewater by membrane filtration. MBRs are extremely efficient for domestic or industrial wastewater treatment, as they can effectively remove organic and inorganic particles and biological material from the wastewater (eds Judd & Judd 2011). When properly maintained and operated, MBRs can remove nutrients and to a certain extent also micropollutants (Capodaglio 2017). Some of the limitations of MBRs include high installation costs of the membranes and the physical structure, high maintenance costs due to frequent fouling of membranes and high energy requirements (eds Judd & Judd 2011).

Anaerobic Digestion

Anaerobic digestion is regarded as an effective and feasible option to treat the blackwater originating from household latrines. Compared to aerobic systems, these compact systems produce a well stabilised sludge in smaller quantities (Parkinson & Tayler 2003). The systems convert the organic matter into biogas (about 40 – 70 % methane), which can serve as a sustainable substitute for energy sources such as firewood (Behrendt et al. 2006, p. 7). The sludge, containing plant nutrients such as nitrogen, phosphorus and potassium, can be either used as liquid fertiliser or separated into a solid and a liquid part with further composting of the solid fraction. Anaerobic digesters, if properly operated, can remove up to 85 – 90 % of the organic load (Parkinson & Tayler 2003, p. 83). According to the study by deGraaff et al. (2010a, p. 108) anaerobic digestion treatment systems, such as the up-flow anaerobic sludge blanket (UASB) reactor, with proper setup, can reach an average COD removal of 74 % for a wastewater having a COD concentration as high as 9,800 mg/L.

Constructed Wetlands

CWs have been proven as a cost-effective method for rural wastewater treatment (Garfí, Flores & Ferrer 2017). CWs are a modified version of natural wetland systems, they include a planted soil filter through which the wastewater flows and is treated through physical processes such as adsorption and biological processes taking place in the biofilm and physical filter. CWs provide efficient removal of organic solids i.e. more than 80 % COD removal and pathogenic microorganisms; however, the phosphorus and nitrogen removal is limited (Wendland & Albold 2010, p. 20). Additionally, to improve the biological activity and to enhance the efficiency of the process, the soil filter is planted with plants such as reed (Behrendt et al. 2006). One of the limitations of CWs is unit area land requirements, ranging from about 2 m^2/PE in warm climates to 12 m^2/PE in cold climates (Capodaglio 2017, p. 5).

Terra Preta Sanitation

TPS is an efficient and cost-effective biowaste/sanitation system based on an ancient Amazonian sanitation practice (Factura et al. 2010). It is an integrated wastewater management concept, which focuses on resource recovery, therefore offering a sustainable solution to major environmental challenges such as poor sanitation, soil depletion and food insecurity (Prabhu et al. 2014). The concept involves conversion of excreta and biowaste to a highly fertile black soil through lactic acid fermentation (LAF), addition of charcoal and woodchips followed by stabilisation via composting or vermicomposting. LAF facilitates the sanitisation and suppression of odour, while the addition of charcoal and woodchips makes the mixture dry enough to be suitable for composting. Subsequent composting techniques such as vermicomposting and thermophilic composting further sanitise the substrate, resulting in nutrient rich humus[2] (ed. DBU 2015; Factura et al. 2010). The final product can be utilised as a fertiliser for non-food crops in forestry or agriculture (Prabhu et al. 2014).

Depending on the available resources, faeces and urine can be either collected separately or combined in the TPS system. In regions where non-flush toilet based sanitation systems are acceptable, urine diverting dry toilets can reap additional benefits for TPS systems, including reduced input of dry material for odour control (ed. DBU 2015). According to Gisi, Petta & Wendland (2014), TPS systems can exist as dry systems (without flush water) and systems with flush water (low-flush). TPS can be integrated into existing toilets by adapting to low-flush toilets, thus reducing the amount of water and volume to be treated. With proper hy-

[2] For more information on TPS, take a look at Volume 3 of the RUVIVAL Publication Series: https://www.ruvival.de/ruvival-volume-3/.

giene measures, pit latrines with liner and a cover to facilitate anaerobic fermentation, can also be adapted to the TPS system (ed. DBU 2015). Dry TPS systems are recommended as it makes it easier to handle the mixture and dehydrate the faeces. However, there exists several projects and research applying TPS with low-flush toilets, acknowledging the use of flush toilets as a standard in most of the regions worldwide (Gisi, Petta & Wendland 2014).

Several secondary treatment options exist with varying treatment efficiencies, resource requirements, advantages and limitations. The appropriateness and effectiveness of each technology however depends on the wastewater input, available financial and technical resources and their desired use.

Disposal Methods

The various disposal methods further improve the quality of the wastewater collected from secondary treatment before finally disposing it. Disposal methods can be simple including evaporation and evapotranspiration, surface water discharge or subsurface discharge. With proper setup and site conditions, the usually preferred method for a single household to dispose wastewater is subsurface soil absorption, because of numerous advantages such as simplicity, cost-effectiveness and stability (Massoud, Tarhini & Nasr 2009). The most common types of subsurface soil absorption systems are discussed as follows.

Traditional Leach Field Systems

The traditional leach field systems are a preferred choice for sites with low water table and where the land is not readily available (Massoud, Tarhini & Nasr 2009). Land treatment systems utilise the plant-soil-water matrix to further enhance the degree of treatment (Crites & Tchobanoglous 1998). The pollutant removal efficiency of these systems is high and one major advantage is that the nutrients are recycled back to the soil (Massoud, Tarhini & Nasr 2009). For areas with impermeable and heavy clay soils, traditional leach field systems are likely to fail, and treatment provided in areas with higher water tables and soils having high permeability is inadequate (Wu et al. 2011).

Raised, Mounded Fill Systems

Fill systems are a modified version of traditional leach field systems and are a replacement for sites where water tables are very high. Gravel sand fill is used to raise the leach above the water table in order to increase the separation distance (Joubert et al. 2005). In mounds, the sandy fill material being used as filler is specified and analysed through sieve analysis. The specified material in the mounds improves the treatment efficiency and is recommended for sites with high infiltration, high water table, porous or creviced bedrock (New York State Department of Health 2012).

There are various treatment options with specific advantages and disadvantages, but there exists no single recommended treatment technology that meets the specific conditions and treatment objectives of every community. However, for a given rural area, the ecological sanitation concept involving source separation of wastewater streams, combined with appropriate decentralised treatment of wastewater streams appears as a sustainable and cost-effective technology for wastewater management.

Integrated Decentralised Wastewater System for Rural Communities

The affordability and appropriateness of the treatment systems are the main issue to consider in the selection process for the most suitable wastewater system for a given community (Grau 1996). In areas with low population density, decentralised systems provide cost-effective treatment of wastewater (Parkinson & Tayler 2003). Decentralisation, with effective localised governance, is progressively perceived as a possibly successful route to ensure availability of clean water and safe sanitation to the world's population, while providing increased opportunities for resource recovery and reuse of wastewater for various purposes (Bieker, Cornel & Wagner, IDRC, Larsen & Maurer, cited in Libralato, Volpi Ghirardini & Avezzù 2012).

Design of Integrated Decentralised Systems

The recommended system is to utilise complex biological principles and natural processes to provide efficient yet cost-effective wastewater treatment, it should be based on a simple design, flexible in treatment capacity, easy to construct, maintain and operate, socially acceptable and pleasing to the eye (Rodale Institute 2013). As shown in Figure 3, the recommended integrated decentralised system is based on the concept of ecological sanitation, involving separation of brown-, grey- and yellowwater through source control schemes and incorporates both traditional and alternative systems in a multi-step process. It focuses on the extraction of nutrients from brown- and yellowwater and reuse of greywater for non-potable purposes. It includes a combination of a septic tank and a CW for the greywater treatment with the effluent being applied to the fields. Depending on the specific use, dry or low-flush toilets, with or without urine diversion, are used for faeces, brownwater or blackwater to be converted into highly fertile black soil, and application of sanitised urine as a soil enhancer. Any effluent from the CWs or the urine sanitisation chamber, that is not utilised, can be finally disposed by subsurface drip infiltration. The integrated system is discussed in detail in the following sections.

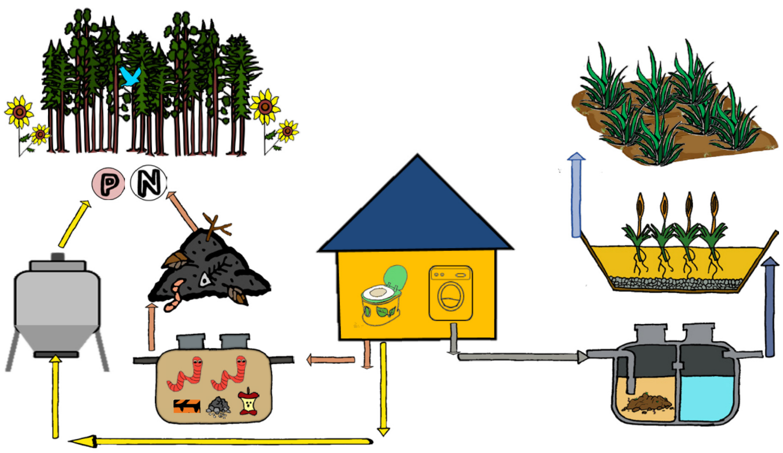

Figure 3 Recommended Integrated Decentralised Rural Wastewater Treatment System

Ecological Sanitation

As suggested by Kjerstadius, Haghighatafshar & Davidsson (2015), effective handling of domestic and municipal waste could be enhanced through the introduction of source control wastewater systems to separate the different streams of grey-, brown- and yellowwater, with focus on resource recovery. Greywater contains some traces of excreta and pathogens, while the concentration of nutrients and pathogens in brown- and yellowwater is significantly high (Tilley et al. 2014). Brown- and yellowwater contain a high percentage of nutrients, generally phosphorus and nitrogen, with a higher concentration of organic matter in relatively lower volumes, therefore making it more preferable for nutrient recovery (ed. DBU 2015). Urine diversion and water saving measures such as low-flush toilets and dry toilets can concentrate the nutrients in the wastewater streams, making the decentralised systems more efficient and cost-effective (Behrendt et al. 2006). With integrated application of source separation, non-conventional conveyance options and extremely low-flush devices, COD values could increase more than tenfold, up to 10 – 15 g/L (Capodaglio 2017, p. 13).

Treatment of Grey-, Brown- and Yellowwater

The most commonly used decentralised system for primary treatment of wastewater is a simple septic tank (Massoud, Tarhini & Nasr 2009). The removal efficiency of septic tanks ranges from 30 – 35 % of BOD, 25 – 35 % of COD and 55 – 65 % of Suspended Solids (SS) (Sperling 2007, p. 221). Septic systems only allow a partial treatment; therefore, there are limitations in the field of local water reuse and resource recovery. However, the system can be modified and integrated with other systems to treat the wastewater more efficiently and adequately (Massoud, Tarhini & Nasr 2009).

The separately collected, less concentrated greywater, after on-site treatment, could be used as an alternative water source (Bakir 2001). It is first treated in a septic tank to remove most of the settleable solids; after which the effluent can be effectively treated in a small horizontal flow CW. According to Rodale Institute (2013, p. 12), with proper setup and operation, CWs can remove 40 – 80 % of the influent nitrogen content and 99.0 – 99.9 % of faecal coliforms, pathogens and viruses present in the wastewater. Moreover, a wetland has an operating energy cost of zero (Rodale Institute 2013, p. 12). The effluent from the CW can then be reused for non-food irrigation purposes; however, more research is required to evaluate the appropriateness of this effluent (Barbagallo et al. 2014).

According to Tilley et al. (2014, p.11, p.142), although the nutrients in the excreta vary according to diet, gender, age, region, etc., faeces contain roughly 12 % nitrogen, 39 % phosphorus and 26 % potassium, while urine contains 88 % nitrogen, 61 % phosphorus and 74 % potassium of the total nutrients excreted. The urine fraction contains the highest percentage of nutrients including potassium, nitrogen and phosphorus, while faeces contain a higher percentage of organic matter (Rose et al. 2015). Due to less dilution that occurs in decentralised systems, the nutrients in the brown- and greywater can be easily and more efficiently recovered and reused. According to Prabhu et al. (2014) TPS provides a great potential for soil enrichment and nutrient recovery from household wastewater. Concentrated faeces from dry or low-flush toilets treated via LAF by adding kitchen waste as a low cost sugar supplement, charcoal and woodchips, followed by vermicomposting or thermophilic composting, results into highly fertile black soil, which can be applied as a fertiliser for agroforestry (ed. DBU 2015). The TPS process results in the stabilisation of waste through the reduction in biological activity, reduction in pathogens, reduction in odour, reduction in total dry matter content and improvement of fertilisation value (Factura et al. 2010).

Source separated nutrient-rich yellowwater can be applied to the soil as fertiliser for agroforestry, providing the opportunity to recover the nutrients and reduce the use of chemical fertilisers (ed. DBU 2015). Health risks linked with use of urine as fertiliser for non-food crop production are very low, provided that no contact takes place with the faeces; however, it should be stored anaerobically in containers made of resistant material, e.g. plastic or high quality concrete, to avoid ammonia emissions (Jönsson et al. 2004). Vinnerås et al. (2008, p. 4067), recommends that the urine can be sanitised by anaerobically storing it for 6 months at 20 °C or higher if any cross contamination takes place[3].

Effluent Disposal

For effluent disposal, with appropriate site, soil and groundwater conditions, subsurface wastewater drip infiltration systems may prove out to be the best option (Massoud, Tarhini & Nasr 2009). The complex ecology of upper layers of local soil provides a natural system to effectively remove, isolate and transform the nutrients, compounds and pathogens that are harmful to the water bodies. Soil systems can effectively transform, sequester or remove compounds such as ammonia, nitrogen and phosphorus compounds, pesticides, suspended and dissolved matter, carbonaceous compounds, heavy metals, medications, cosmetics and pathogens such as faecal coliforms and viruses. The disposal of the remaining effluent from CWs and the urine sanitisation chamber to the soil system further improves the water quality (Rodale Institute 2013).

Sustainability of Integrated System

The three phases of wastewater management: collection, treatment and disposal can have huge implications on the environment as well as the economy, at local and global scales. Sustainability of wastewater treatment technology is the measure of the system's ability to be environmentally sound, economically affordable and socially acceptable (Capodaglio 2017). To assess the sustainability of the recommended integrated system, sustainability criteria as shown in Figure 4 (see p. 55) should be considered.

The integrated decentralised system with source separation provides the opportunity for energy savings and resource recycling. The potential of the system is discussed as follows.

[3] For more information on Urine Utilisation, take a look at Volume 3 of the RUVIVAL Publication Series: https://www.ruvival.de/ruvival-volume-3/.

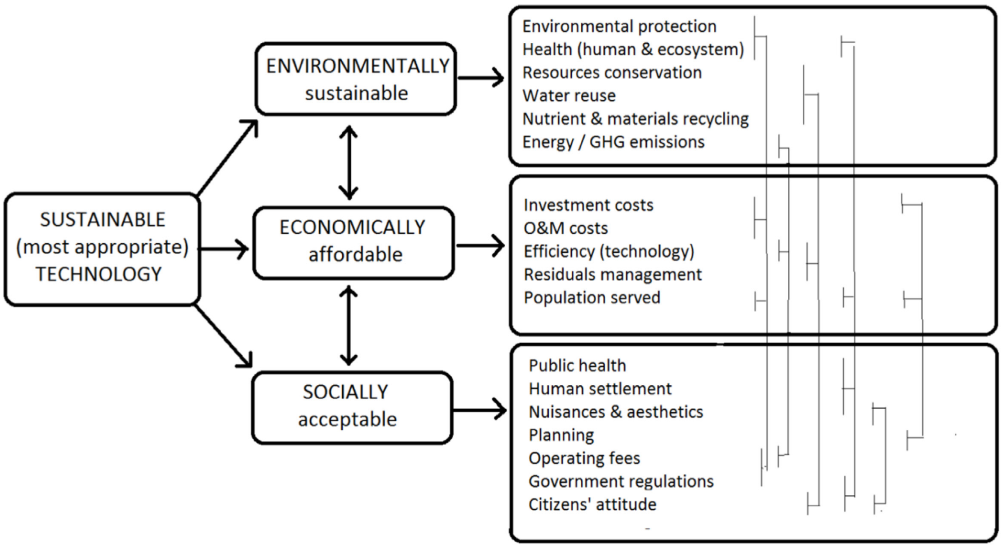

Figure 4 Integrated System Sustainability Criteria (Capodaglio 2017, p. 7)

Potential for Energy Savings

The recommended integrated decentralised system provides great potential for energy savings. Tervahauta et al. (2013) conducted a study on Dutch conditions to evaluate the primary energy consumption of centralised and decentralised systems, with and without source separation of wastewater streams. Their observation concluded that centralised sanitation systems consume the most primary energy with 914 MJ/a per person. Source separation of blackwater and greywater along with kitchen waste in a decentralised system can result in a reduced energy consumption of 767 MJ/a per person and 522 MJ/a per person by including the indirect energy gains from water savings, reuse and nutrient recovery. Source separation of urine, faeces and greywater along with kitchen waste in a decentralised system with gravity based toilets can result in the reduced energy consumption of 567 MJ/a per person, which is further reduced to 208 MJ/a per person by including the indirect energy gains (Tervahauta et al. 2013, p. 1023).

Potential for Water Savings

Conventional centralised wastewater treatment systems are usually not efficient when it comes to water use. In fact, brown-, grey- and yellowwater usually end up in the sewage system, and are then treated in high capacity treatment plants, leading to water loss due to leakage (Rutsch, Rieckermann & Krebs 2006). Moreover, these systems also require additional water for the transport of wastewater to the centralised treatment facility. In the most effective decentralised wastewater treatment system, water savings can be achieved by minimising the wastewater component as soon as possible; and separating, treating and reusing the different wastewater types (US EPA 2015). The recommended application of marginally treated greywater for flushing purposes allows savings of potable water. The greywater can also be reused on-site for non-food irrigation since it contains nutrients useful to plants (Al-Jayyousi 2003). According to Friedler (2004, p. 997), the use of decentralised treatment systems with greywater reuse can save up to 65 – 70 L/d per person of potable water.

Potential for Nutrient Recovery

Around 90 % of the nitrogen and 90 % of the phosphorus in the excreta are contained within the blackwater (Jönsson et al., cited in Spångberg, Tidåker & Jönsson 2014, p. 210). There lies a great potential to recover nutrients from household wastewater through source control techniques and decentralised wastewater systems. Malisie, Prihandrijanti & Otterpohl (2007, p. 142) reported a possible recovery of up to 86 % of nitrogen, 21 % of phosphorous and 69 % of potassium from urine and 12 % of nitrogen, 68 % of phosphorous and 20 % of potassium from faeces by using urine diverting toilets. Faeces and urine contain nutrients that are essential for plants and can replace the need for artificial fertilisers. According to deGraaff et al. (2010b, p. 7) one tenth of the existing worldwide production of anthropogenic phosphorous fertiliser can be fulfilled by recovering phosphates from blackwater using struvite precipitation.

Wielemaker, Weijma & Zeeman (2018) analysed the implication and possibilities of a closed loop resource cycle for integrated decentralised sanitation, with focus on nutrient recovery and urban agriculture. By recycling and reusing the nutrients contained within the domestic wastewater, a possible demand minimisation of phosphorus by 100 % and of nitrogen and carbon compounds by 65 – 85 % for urban agriculture can be reached (Wielemaker, Weijma & Zeeman 2018, p. 426).

Jönsson et al. (2004, p. 1) concluded in their research that direct application of urine from one person to the soil can fertilise 300 – 400 m^2 (N-fertilisation) and 600 m^2 (P-Fertilisation) of land in a year respectively. The TPS systems can further enhance the availability of nutrients to be applied to the soil. Krause et al. (2015, p. 4045) investigated the potential of nutrients recycling by TPS and found that TPS compost contains 3.6 times more phosphorus than the normal compost.

The adoption of the recommended integrated decentralised wastewater treatment system provides a great potential to recover and re-use valuable resources from wastewater while effectively treating the wastewater. It could significantly and sustainably help to close resource use loops in wastewater management.

Case Studies of Integrated Decentralised Wastewater Management

The concept of integrated decentralised wastewater management has been implemented in various developed and developing regions of the world. Some of the case studies are summarised as follows.

Hamburg Water Cycle in Jenfelder Au, Germany

The integrated decentralised wastewater management concept is realised on a big scale within the urban development project 'Jenfelder Au' in the eastern part of Hamburg. Jenfelder Au is a project under construction, and is expected to inhabit approximately 2,000 residents on 35 ha of land (Augustin et al. 2014, p. 13). The first residents moved into their flats in spring 2017; however, more buildings are still being constructed. The sanitation system is based on the idea of a separate collection of wastewater streams and the use of water saving toilets i.e. vacuum toilets. The system is designed to have separate streams for rainwater, blackwater and greywater. As shown in Figure 5 (see p. 58), the blackwater is treated separately by anaerobic treatment and results in the production of biogas, whose heat and energy recovery is cycled back to the residential areas. Separately collected greywater is treated and released back to water bodies. The digestate from the biogas can then be applied in fields as a biofertiliser to increase the productivity of the soil. One important feature of the Jenfelder wastewater system is the rainwater reuse. The rainwater flows into retention ponds, thereby reducing the burden on the sewer network. The retention ponds and lakes can also serve as flood protection besides adding to the attractiveness of the area (Hamburg Wasser 2018).

According to the European Commission (2010), the innovative system will comprise of approximately 1,000 vacuum toilets and a vacuum pipe system. It is expected to reduce water consumption by 7.3 m³/a per person. A biogas combined heat and power generation plant is expected to generate approximately 800 kWh/a per person. Overall, as expected, the system will save around 500,000 kg/a of CO_2 equivalents and Jenfelder Au will be self-sufficient in terms of wastewater treatment and heat supply. It is expected to meet 50 % of its energy demand locally.

Ecological Sanitation Pilot Plant in Surabaya, Indonesia

The ecological sanitation concept is adopted in a wastewater system in Surabaya, East Java, Indonesia. Household wastewater is separated at the source into brown-, yellow- and greywater. Source separated yellowwater is stored in an anaerobic storage tank at room temperature for 6 months for sanitisation. The brownwater component of the stream is collected in a solid-liquid separation tank, where a fish net hanging in the tank separates the solid part of the brownwater. The liquid part and greywater is further treated by a small CW. The circular flow of the water and nutrients in the Surabaya plant is demonstrated in Figure 6 (see p. 58). To achieve the recommended sanitisation levels, vermicomposting with specific types of earthworms is utilised to stabilise the organic material and convert it into humus to be used as a fertiliser. After only one month of vermicomposting faecal matter, a good quality compost is produced with a suitable C/N ratio, while containing very low amounts of *E.coli* (Malisie, Prihandrijanti & Otterpohl 2007).

Malisie, Prihandrijanti & Otterpohl (2007) conducted research to assess the potential of nutrient reuse from a source separation domestic wastewater system in Indonesia. Small-scale cultivation experiments with baby rose (*Rosa Multiflora*) were carried out to assess the potential of compost to be used as a fertiliser. This plant was chosen based on its rapid growth (2 – 3 months) and its ability to be planted in every season. The growth rate of baby roses with urine and faecal fertilisers was observed; the results concluded that the application of urine fertiliser gives the best and fastest growth to the baby roses, acting as a quick fertiliser because of its higher nitrogen content compared to other fertilisers. The research revealed that human excreta could effectively substitute the use of chemical fertiliser, after complete sanitisation.

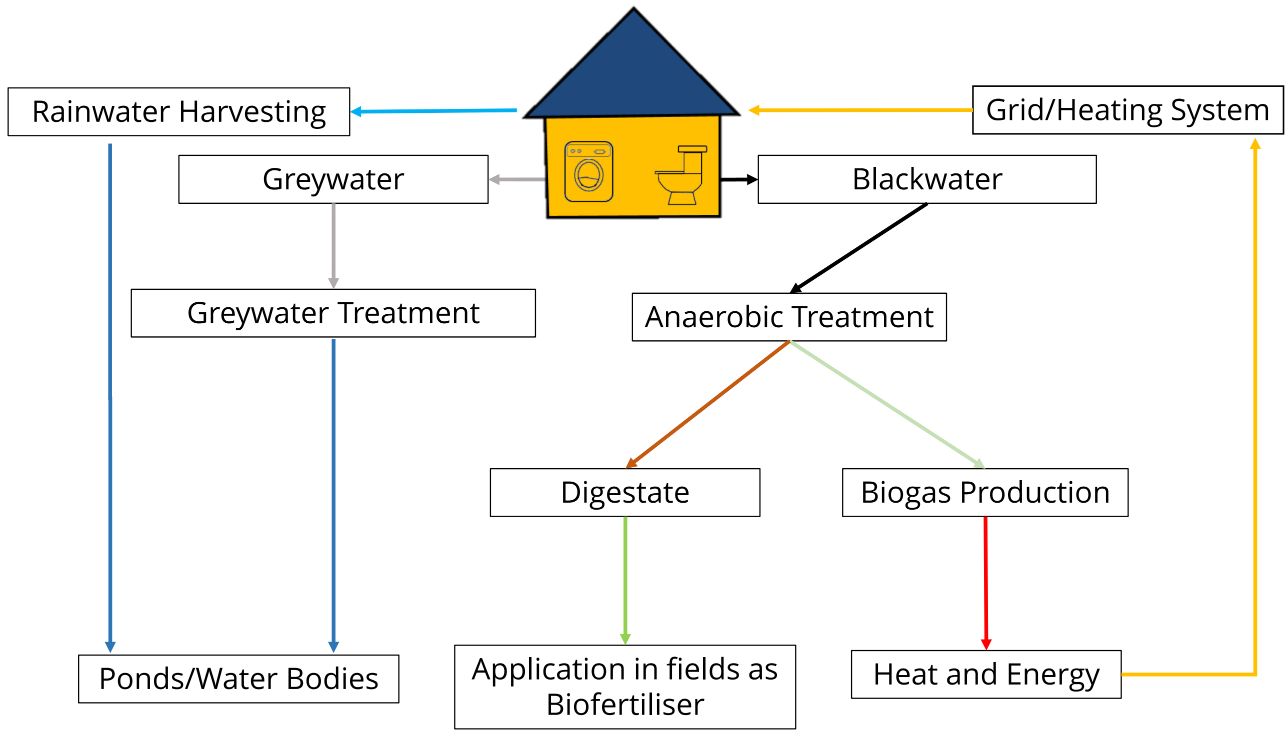

Figure 5 Efficient Recycling of Different Streams of Wastewater, Based on Hamburg Wasser (2018)

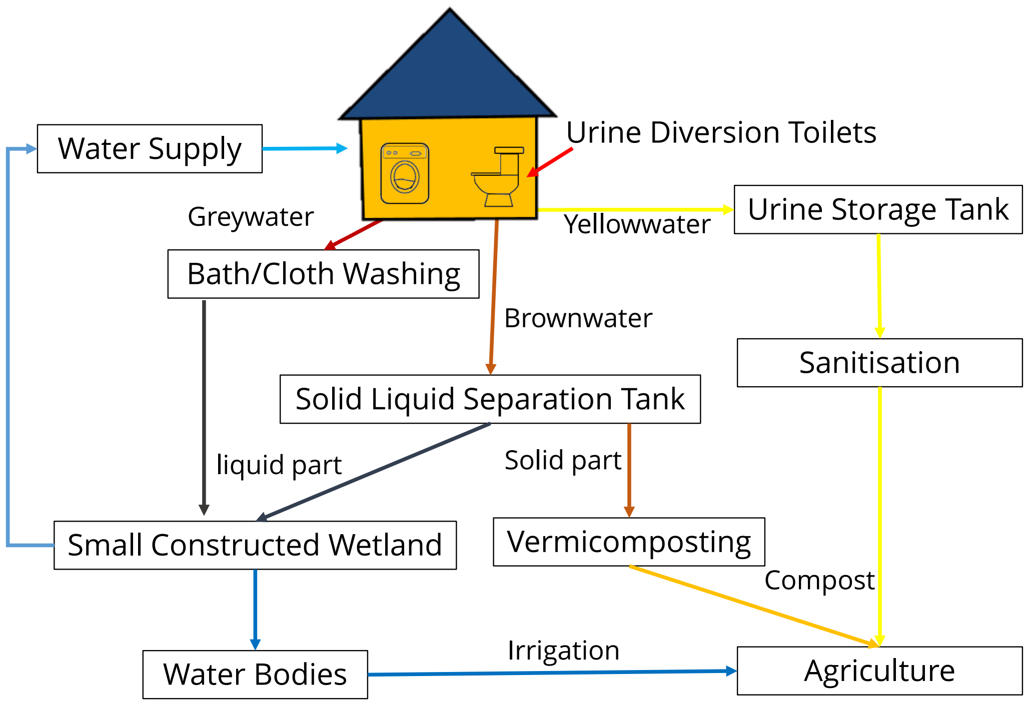

Figure 6 Circular Flow of Water and Nutrient at the Pilot Plant in Surabaya, Based on Malisie, Prihandrijanti & Otterpohl (2007).

Integrated decentralised wastewater treatment systems have been implemented in different rural and peri-urban regions of the world, and case studies have revealed that they constitute a sustainable and cost-effective treatment option for rural wastewater.

Conclusion

This paper analysed the possibilities of decentralised wastewater treatment in comparison to centralised wastewater treatment in rural communities. The technical, economic and environmental aspects of decentralised rural wastewater management with a focus on resource recovery were discussed. Based on a literature review, decentralised management based on the ecological sanitation concept appeared as a sustainable and economically sound option for wastewater treatment in rural areas, with a potential for nutrient recovery, water reuse and energy savings.

As highlighted throughout the paper, there exists no single universal solution to the technological, financial, social and environmental issues related to wastewater treatment and management. However, the decisions regarding selection, construction, maintenance and operation of wastewater treatment systems, based on the principles of sustainability and circular economy, could tackle the problems sensibly without exporting them to future generations. In the light of extensive research, an integrated decentralised wastewater system comprising source separation, a conventional septic tank, a CW, TPS with or without urine diversion and a subsurface drip irrigation system is recommended for rural wastewater treatment.

While the results of publications and case studies showed that in rural communities decentralised wastewater systems are a good alternative to centralised wastewater systems, further research based on financial, economic and environmental feasibility with regards to water savings, nutrients recovery and energy production is required for developments where centralised wastewater treatment plants are already in place.

Picture Credits

Figure 1 (p. 40) Proportion of National Population Using at least Basic Sanitation Services <https://www.unicef.org/publications/files/Progress_on_Drinking_Water_Sanitation_and_Hygiene_2017.pdf> by UNICEF & WHO is licenced under CC BY-NC-SA 3.0 IGO <https://creativecommons.org/licenses/by-nc-sa/3.0/igo>.

Figure 2 (p. 43) Different Types of Wastewater Treatment Systems
Based on Libralato, Volpi Ghirardini & Avezzù (2012).

Figure 3 (p. 52) Recommended Integrated Decentralised Rural Wastewater Treatment System <https://nbn-resolving.org/ urn:nbn:de:gbv:830-88222483> by Usama Khalid is licensed under CC BY-SA 4.0 <https://creativecommons.org/ licenses/by-sa/4.0/>.

Figure 4 (p.55) Integrated System Sustainability Criteria
'Issues categories, subcategories, and their relationships, which need addressing in a sustainability evaluation' <https://www.mdpi.com/2079-9276/6/2/22> by Capodaglio is licenced under CC BY <http://creativecommons.org/licenses/by/4.0/>.

Figure 5 (p. 58) Efficient Recycling of Different Streams of Wastewater
Based on Hamburg Wasser (2018).

Figure 6 (p. 58) Circular Flow of Water and Nutrient at the Pilot Plant in Surabaya
Based on Malisie, Prihandrijanti & Otterpohl (2007).

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