Energy Reports 5 (2019) 398–408

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

A comparison of DC- versus AC-based minigrids for cost-effective electrification of rural developing communities

Nicholas Nixon Opiyo

Centre for Engineering and Renewable Energy, School of Computing, Engineering and Intelligent Systems, Ulster University, Magee Campus, Londonderry, BT48 7JL, United Kingdom

HIGHLIGHTS

- Power conversion losses are the main pints of losses in minigrids.
- DC minigrids avoid many conversion stages seen in AC minigrids.
- Use of DC-inherent appliances with DC power lead to even better performances.
- DC systems with decentralized power storage are the preferred paths to rural electrification.

ARTICLE INFO

Article history:
Received 22 February 2019
Received in revised form 1 April 2019
Accepted 2 April 2019
Available online 9 April 2019

Keywords:
Minigrids
DC-coupled
AC-coupled
Conversion losses

ABSTRACT

Sub-Saharan Africa continues to suffer energy poverty due to low grid expansion rates necessitated by low economic activities in those regions, sparse population distribution coupled with low household load demands, and insufficient power generation. On the other hand, small solar power microgeneration systems have emerged as potential alternatives to grid electrifications, enabling households to make modest investments into their power systems, and to modify those systems according to their changing economic and power demand circumstances. For rural social-economic development, electricity-beyond-lighting is needed. Without the grid, the only alternative is minigrids based on locally available renewable energy resources. In this work, we compare the merits and demerits of DC and AC coupled systems as pertains to costs, efficiencies, and overall performances. Research shows that power conversion stages are the biggest points of power losses in minigrids and therefore avoiding many conversion stages lead to improved overall system efficiencies. Research also shows that the best performances are realized when DC-inherent appliances are supplied with power from DC-coupled networks, supplied by distributed DC power generators such as PV. Simulation results show that when given choices, consumers choose to connect to DC networks with decentralized storage due to lowest operating costs, ease of expansion, and overall better performances when compared to other networks.

1. Introduction

Today, about 588 million people still lack access to electricity in rural sub-Saharan Africa because of insufficient power generation, insufficient and inefficient power transmission and distribution networks to rural areas, high poverty index and thus unaffordability of available electrification options, very low household power demands coupled with very low productive use of electricity in rural areas leading to delayed investments in transmission and distribution networks to those areas, and unreliability of the national electricity grid, with frequent unscheduled blackouts and brownouts, leading to damages to appliances, lost revenues, and high power costs (IEA, World Energy Outlook, 2018). Table 1 shows electricity access in 2018.

There are three possible paths to rural electrification and these are: (1) through extension of existing national grids to those areas, (2) through minigrids or microgrids, and (3) through standalone power microgeneration systems. Only 30% of the 588 million people can be cost-effectively electrified through path 1 (IEA, World Energy Outlook, 2018). The remaining 70% would be cost-effectively electrified through path 2 or 3, i.e., through decentralized and localized power generation systems (International Energy Agencyf, 2016). Specifically, 52.5% would be cost-effectively electrified through minigrids/microgrids while 17.5% would be cost-effectively electrified through standalone systems (International Energy Agencyf, 2016). The modular nature of microgeneration technologies allows for phased project implementations, enabling households and communities to initiate modest power generation programs, and to modify their systems according to

---

E-mail address: N.Opiyo@ulster.ac.uk.

https://doi.org/10.1016/j.egyr.2019.04.001

Table 1
Electricity access 2016 — regional summary.
Source: IEA, World Energy Outlook (2018).

Region	Rate of access			Population without access (million)
	National	Urban	Rural	
	2016	2016	2016	2016
World	**86%**	**96%**	**73%**	**1060**
Developing countries	**82%**	**94%**	**70%**	**1060**
Africa	**52%**	**77%**	**32%**	**588**
North Africa	100%	100%	99%	<1
Sub-Saharan Africa	43%	71%	23%	588
Developing Asia	**89%**	**97%**	**81%**	**439**
China	100%	100%	100%	–
India	82%	97%	74%	239
Indonesia	91%	99%	82%	23
Other Southeast Asia	89%	97%	82%	42
Other Developing Asia	73%	87%	65%	135
Central and South America	**97%**	**98%**	**86%**	**17**
Middle East	**93%**	**98%**	**79%**	**17**

Table 2
Lists some potential applications of DC minigrids in developing communities.

Applications	Examples
Disaster relief	• Refugee camps • Disaster zones such as landslides, flooding, collapsed construction sites, war zones, etc. • Drought relief to pump water for human/animal use and irrigation in drought stricken regions
Hospitality industry	• Isolated game camps, lodges, and reserves • Isolated hotels and resorts
Productive use of electricity in rural villages	• Agriculture and food production (irrigation, posho mills, fencing, etc.) • Small manufacturing enterprises (carpentry, welding, tailoring, looming, etc.) • Service sector (bars, restaurants, barber shops and salons, charging stations for mobile phones, etc.) • Food preservation (refrigeration)
Common use	• Public lighting • Schools, • Health centres, etc.

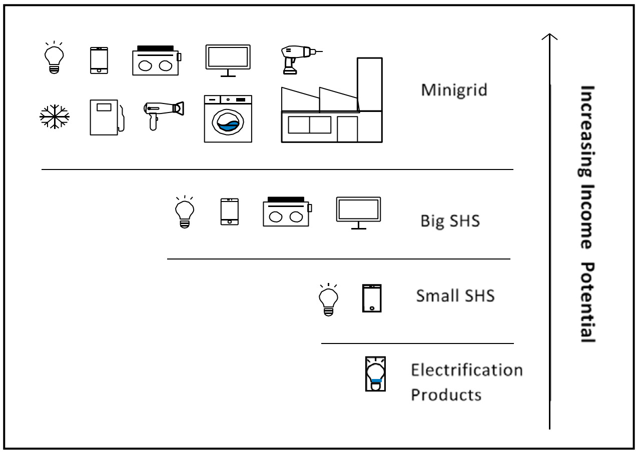

Fig. 1. Energy ladder.

their changing energy needs, and climb the energy ladder as shown in Fig. 1.

Depending on local resources, capacities, designs and technologies used, microgeneration systems could provide the final solutions to rural electrification in many developing nations and entrench green economies in the process. In fact, it is estimated that there will be almost 400 TWh of installed microgeneration capacity by 2030, about 40% of new installed capacities towards universal electrification in developing nations (International Energy Agencyf, 2016).

Most rural households require electricity basically for lighting and to power small electrical appliances such as mobile phone chargers, small TVs, and stereo systems (Opiyo, 2016, 2015). These households are mainly powered through small solar electricity microgeneration systems, commonly known as solar home systems (SHS). Those connected to grid electricity also have enough power for irons, electric kettles, microwaves, fans, and refrigerators. Even though the grid expansion has outpaced population growth in many countries, this is not the case in sub-Saharan Africa. Between 2010 and 2017, the grid coverage only increased by 7%, leading to less than 40% of overall coverage (Lighting Global, 2016). Moreover, the grid still remains highly unreliable, with blackouts a constant occurrence in these regions. The slow grid growth, together with unreliability of the grid, rapid population growth, and small SHS requiring replacements every 2–4 years, has made the size of the potential market for off-grid solar sector to stay largely stagnant, even with exponential growth in SHS sales and installations in the region (Lighting Global, 2016).

2. Minigrids

Using electricity basically for lighting and to power small household electronic appliances does not stimulate rural economic growth. For this, access to grid-level electricity, either through the national grid or through minigrids, is needed. Since grid growth is slow due to low rural power demands, and due to unreliability of existing grid networks, minigrids based on locally available renewable energy resources, in this case solar, are emerging as most readily available means of providing grid-level electricity to these regions. Minigrids are defined as a locally confined and independently controlled electric power grids in which distribution architectures integrate distributed loads and distributed energy resources (Opiyo, 2018b,a). They offer many advantages over other electrification options in that when compared to national utility grids, they are cheaper to put up, with shorter lead times, sized to match local demands, and are modifiable with increasing demands or changing technologies, while when compared to solar home systems, they offer access to power for productive use as schematically shown in the energy ladder (Fig. 1) (Opiyo, 2018b,a). Minigrids have many other potential applications beyond powering households and small businesses. The main ones include disaster relief, remote hospitality industry such as safari lodges, productive use of electricity in rural villages, and powering rural social centres, schools, and health centres, as summarized in Table 2.

Minigrids can be divided into two groups: minigrids with capacities between 10 kW and 10 MW and microgrids with capacities below 10 kW. Each minigrid comprises of the following two operational systems: small power production and small power distribution. The small power production comprises of generation and storage subsystems while small power distribution comprises of distribution and consumption subsystems. The generation subsystem includes the power generator, power conditioners, and power management technologies while the distribution subsystems include grid networks for transporting power to individual consumers. Based on design, capacity, and technology, these systems could be AC, DC, earth return, single-phased, or three-phased. The consumption subsystems comprise all the equipment at the end consumer side, i.e. metering, wiring, grounding, and electrical appliances.

2.1. DC vs. AC minigrids

Minigrids can be DC-coupled, AC-coupled, or a combination of the two; a grid using a DC bus avoids many of the power conversion steps required when using an AC bus, leading to higher energy efficiency and cost-saving. Traditionally, AC enabled efficient voltage transformation and high-voltage power transmission over long distances. Recently however, technology advances have led to highly efficient AC/DC and DC/DC converters, making high-voltage DC long-distance bulk power transmission more efficient (Opiyo, 2018b,a; Vallve and Serrasolses, 1997). In summary, DC power distributions over DC networks have many benefits including (Opiyo, 2018b,a; Vallve and Serrasolses, 1997):

- Higher power system efficiency due to fewer AC/DC or DC/AC conversion losses
- DC systems tend to be more modular and scalable than AC systems because DC converters are easier to control and to parallel. This allows for more flexibility in systems designs and expansions, and thus more effective capital investment management
- DC system components tend to be more compact than equivalent AC components because of higher efficiency and due to not being frequency dependent
- Lower capital costs due to fewer electronic components used (no inverters),
- Higher survivability (lower power control system complexity) when subjected to external and internal disturbances due to elimination of synchronization requirements associated with AC systems
- Most distributed energy sources and storage devices have inherently DC outputs, making DC architectures more natural options for their integrations
- Most modern loads require a DC input; even AC classical loads like induction motors rely on inherently DC input variable speed drives (VSDs) to achieve a more efficient and flexible operation.
- Availability: DC is several times more reliable than AC according to NTT data from 30,000 systems due to fewer electronic components (points of failure) used (no inverters) (Chaurey and Kandpal, 2010)
- The market is ready for DC minigrids; falling PV costs, falling energy storage costs, and rise in pay-as-you-go platforms have created an inductive environment for DC minigrids to thrive in.

Due to lower power and energy ratings, stability issues are more prevalent in minigrids than in utility grids. Analyses of stability issues in AC-coupled communal grids follow the same concepts as with utility grids, i.e.:

- Voltage and frequency values need to both be regulated through active and reactive power control
- If a decentralized power source is a traditional synchronous generator with an AC output, and is connected directly to the utility grid without power electronic interfaces, stability is controlled through the machine shaft's torque and speed control

In DC systems there are no reactive power interactions which suggests that there are few stability issues; system control seems to be oriented towards voltage regulation only.

2.2. Power losses in DC vs. AC systems

Power losses in minigrids are mainly due to cable losses, voltage (IR) drops, and rectifier (conversion) power losses. Power losses in cables occur due to resistance in both DC and AC systems, with additional stress on the dielectric in AC systems. In DC systems, these can be modelled as (Laudani and Mitcheson, 2017):

$$\Delta P_{DC} = 2 \cdot R \cdot \frac{P^2}{V_{DC}^2} \tag{1}$$

where P is the transmitted power, R is the resistance per core, and V_{DC} is the voltage level.

In single-phase AC systems, power losses are modelled as (Laudani and Mitcheson, 2017):

$$\Delta P_{1\emptyset} = 2 \cdot R \cdot \frac{P^2}{V_{rms}^2 \cdot \cos^2 \emptyset} \tag{2}$$

where $\emptyset$ is the phase angle.

The ratio of (1) to (2) is given by:

$$\frac{\Delta P_{DC}}{\Delta P_{1\emptyset}} = \frac{V_{rms}^2}{V_{DC}^2} \cos^2 \emptyset \tag{3}$$

From (3), we can infer that DC systems perform better than AC systems with guaranteed equal transmitted power for the same load with very low stress on the dielectric.

Voltage (IR) drop in DC systems is given by (Laudani and Mitcheson, 2017):

$$\Delta V_{DC} = 2 \cdot R \frac{P}{V_{DC}} \tag{4}$$

While in single-phase AC systems it is given by (Laudani and Mitcheson, 2017):

$$\Delta V_{1\emptyset} = 2 \cdot \frac{P}{V_{rms}} (R + X \cdot \tan \emptyset) \tag{5}$$

The ratio of (4) to (5) is given by:

$$\frac{\Delta V_{DC}}{\Delta V_{1\emptyset}} = \frac{R}{\sqrt{2} \cdot (R + X \cdot \tan \emptyset)} \tag{6}$$

From (6), we can see that IR drop in DC systems is lower than that in AC systems for DC voltage taken at AC peak voltage.

In addition to transmission losses, there are also conversion losses due to rectifiers, in case of AC power supplying DC loads (Hammerstrom, 2007; Techakittiroj and Wongpaibool, 2009). Diodes in rectifiers suffer power losses due to built-in potential and non-zero on-state resistance. These losses in AC power supplied systems can be modelled as (Laudani and Mitcheson, 2017):

$$P_L = D \cdot \left(V_{bi} + R_{on} \cdot I_f\right) \cdot I_f \tag{7}$$

where D is the duty cycle, V_{bi} is the built-in potential, R_{on} is the on-state resistance, and I_f is the forward current. In addition to the power losses, voltage and current harmonics also occur due to the input rectifier, a phenomenon that can all be avoided if DC power supply was used, and thus no need for power factor correction.

Power losses in minigrids mainly occur in power conversion stages, making losses occurring in cables negligible, and therefore the fewer the conversion stages the higher the overall system efficiency. The efficiency of AC/DC converters increases with the output power and also changes with loading conditions; at low-load conditions the efficiency can be very low, wasting a large amount of energy that goes through the converter as heat (Eerge Alliance, 0000). Research shows that the average efficiency

Table 3
AC/DC converter efficiencies.

Loading condition	Dedicated AC/DC power supplies MAX efficiency	Bulk AC/DC power supplies MIN efficiency
20%	76.3	84.7
40%	82.5	88.7
60%	84.7	90.1
80%	85.7	90.2
100%	85.9	89.8

of individual AC/DC converters for individual appliances is 68% while that of bulk/centralized converters is 90% (Hammerstrom, 2007). A single centralized conversion stage, as opposed to many dedicated conversion stages, reduce points of losses and thus improves reliability and overall efficiency (Lawrence Berkeley National Laboratory, 0000). If AC/DC power supplies with a power rating under 100–150 W are considered as dedicated power supplies and the AC/DC power supplies rated above 1000–1500 W are considered as bulk power supplies, the efficiency for AC/DC power supplies can be tabulated as shown Table 3 (Lawrence Berkeley National Laboratory, 0000).

For DC/DC converters, where the first conversion stage in AC/DC converters is removed, the overall efficiency is about 2.5% higher, and thus a dedicated DC/DC power supply is 88.4% efficient while a bulk DC/DC power supply is 92.3% efficient (Lawrence Berkeley National Laboratory, 0000). Many household appliances and electronics used in rural households with SHS are inherently DC. To power these appliances from AC sources, power is first converted to DC, then a DC/DC converter is used to reduce the voltage to the level required by the appliance. All these conversion stages are points of power losses. Things could be made worse if the original AC source was from a conversion of DC power generators such as PV systems, leading to an increase in the number of dedicated power conversion stages. If the power was supplied directly form a DC source generator, this would eliminate DC/AC/DC/DC conversion stages, leading to improved efficiency and reliability (Lawrence Berkeley National Laboratory, 0000). Each AC designed appliance has a DC counterpart, with potential improvements in overall efficiencies when supplied from DC sources. Some of these alternative technologies are summarized in Table 4 (Techakittiroj and Wongpaibool, 2009; Mohan, 2012; http, 0000a):

Table 5 shows estimated energy savings from using DC technologies to replace AC-inherent technologies (Vossos et al., 2017b). For a typical residential household, use of DC-technologies in DC-inherent appliances lead to an average saving of 33% in energy consumption. The greatest savings are seen in the usage of LED bulbs as opposed to incandescent bulbs, with reported savings of up to 73% in energy usage. Use of variable speed drives in combination with heat pumps, as opposed to resistance based heating, leads to reported savings of up to 50% in energy usage. Similarly, use of brushless DC permanent magnet motors with variable speeds, as opposed to induction motors with single speed compressors, lead to reported energy savings of up to 30%.

Table 5
Potential energy from switching to DC-inherent technologies.

Appliance	DC-technology replacement	Estimated energy savings
Lighting	LEDs	73%
Cooking	Induction	12%
Home electronics	Digital electronics	0%
Heating	VSD/Heat pump	50%
Cooling	BDCPM variable speed	30%
Mechanical work	BDCPM motor	30%
Average (residential)		**33%**

Table 6
Estimated energy savings by switching to DC-inherent technologies and by avoiding AC/DC conversions.

Appliance	Energy savings by switching to DC-inherent technologies	Energy savings by avoiding AC/DC conversion stages
Lighting	73%	18%
Cooking	12%	12%
TV	0%	15%
Stereo	0%	21%
DVD/CD	0%	31%
Heating	50%	12%
Cooling	30%	13%
Mechanical work	30%	13%
Average (residential)	**33%**	**14%**

Table 6 estimates the energy savings by switching to DC-inherent technologies run on AC power source and energy savings from avoided AC/DC power conversion losses (Garbesi et al., 2011; http, 0000b; Vossos et al., 2017a). We can infer from the table that use of DC-inherent technologies lead to move savings in power consumption, and this is mainly due to avoidance of AC/DC and DC/AC power conversion stages.

Table 7 compares the number of conversion stages and efficiencies of appliances based on traditional technologies and on new technologies, supplied through centralized AC or DC power sources (Lawrence Berkeley National Laboratory, 0000; Techakittiroj and Wongpaibool, 2009). From the table, DC-inherent appliances perform better when supplied through DC power than when supplied through AC power due to reduced conversion stages. The weighted average shows that AC-designed appliances, whether DC-inherent or not, perform better when supplied with grid electricity, than do new technologies.

Using distributed power sources that naturally provide DC voltage, the advantage of DC distribution over AC distribution becomes more evident. Table 8 compares the number of power conversion stages and efficiencies of different new-technology appliances with distributed AC and DC power sources. New DC-based technologies, when supplied with DC power from DC-based distributed sources, perform 13.1% more efficiently that when supplied with AC power.

Table 4
Old AC-inherent appliances and DC technologies that can be used to replace them.

Appliance	AC-technology	DC-internal technology
Lighting	Incandescent	Electronic (fluorescent or LED)
Cooking	Electric resistance	Induction
Home electronics (TV, Stereo etc.)	Digital electronics	Digital electronics
Heating	Electric resistance	Variable-speed drives (VSDs) driven by brushless DC permanent magnet (BDCPM) motors, heat pump
Cooling	Induction motor, single speed compressor	Variable-speed drives (VSDs) driven by brushless DC permanent (BDCPM) motors.
Mechanical work	Induction motor	BDCPM motor

Table 7
Comparison of conversion stages and efficiencies of traditional and new technology appliances supplied with centralized DC and AC power.

Appliance		AC supply			DC supply		
End use	Technology	Bulk conversions	Dedicated conversions	Efficiency (%)	Bulk conversions	Dedicated conversions	Efficiency (%)
Lighting	Old: CFLs	0	2	83.6	1	0	92.6
	New: LEDs	0	1	85.7	1	0	90.1
TV	Old: Digital electronics	0	2	83.6	1	0	92.6
	New: Digital electronics	0	1	85.7	1	0	95
Cooking	Old: Resistance based	0	0	100	1	0	95
	New: Induction	2	0	87.5	2	0	87.5
Stereo	Old: Digital electronics	0	2	83.6	1	0	92.6
	New: Digital electronics	0	1	85.7	1	0	95
Mobile phone charging	Old: Digital electronics	0	2	83.6	1	0	92.6
	New: Digital electronics	0	1	85.7	1	0	95
Heating or ventilation	Old: Resistance based	0	0	100	1	0	95
	New: VSD based	2	0	87.8	2	0	87.8
Other	Old technology	–	–	100	–	–	100
	New technology	–	–	100	–	–	100
Weighted average	Old technology	–	–	**91.5**	–	–	**94.5**
	New technology	–	–	**88.5**	–	–	**90.6**

Table 8
Comparison of conversion stages and efficiencies of new technology appliances supplied with decentralized DC and AC power.

Appliance		AC supply			DC supply		
End use	Technology	Bulk conversions	Dedicated conversions	Efficiency (%)	Bulk conversions	Dedicated conversions	Efficiency (%)
Lighting	LEDs	1	1	83.6	2	0	92.6
TV	Digital electronics	1	1	83.6	2	0	92.6
Cooking	Induction	3	0	72.9	2	0	97.5
Stereo	Digital electronics	1	1	83.6	2	0	92.6
Mobile phone charging	Digital electronics	1	1	83.6	2	0	92.6
Heating or ventilation	VSD based	3	0	92.9	2	0	97.5
Other	–	–	–	100	–	–	100
Weighted average	–	–	–	**81.6**	–	–	**94.7**

Table 9
A comparison of efficiencies of new technology appliances supplied with centralized and decentralized DC and AC power.

Appliance		Centralized power		Decentralized power	
		AC	DC	AC	DC
End use	Technology	Efficiency (%)	Efficiency (%)	Efficiency (%)	Efficiency (%)
Lighting	LEDs	85.7	90.1	83.6	92.6
TV	Digital electronics	85.7	95	83.6	92.6
Cooking	Induction	87.5	87.5	72.9	97.5
Stereo	Digital electronics	85.7	95	83.6	92.6
Mobile phone charging	Digital electronics	85.7	95	83.6	92.6
Heating or ventilation	VSD based	87.8	87.8	92.9	97.5
Other	–	100	100	100	100
Weighted average	–	**88.5**	**90.6**	**81.6**	**94.7**

In summary, Table 9 compares the efficiencies of new DC-based appliance technologies when supplied with DC or AC power from centralized vs. distributed power sources. From the table, we can conclude that DC systems supplied by decentralized DC power are over 4% more efficient than those supplied by centralized DC power. The difference in efficiencies increases to over 13% when compared to those supplied by centralized AC power. This is due to elimination of many power conversion stages.

3. Modelling DC vs. AC minigrids

Four different minigrids of same sizes are modelled and simulated in Matlab/Simulink to compare their costs and ease of expansion based on the total number of conversion stages. The minigrids are classified as: (a) DC minigrid with decentralized storage, (b) DC minigrid with centralized storage, (c) AC minigrid with decentralized storage, and (d) AC minigrid with centralized storage. Each minigrid modelled comprises 4 PV arrays, each rated 100 kWp, for a total output of 400 kWp at 1000 W/m^2 irradiance. 4 different arrays are used instead of 1 in order to highlight the significance of decentralization. It is assumed that all the minigrid have the same distributing network (cable) length and therefore cable costs are the same. It is also assumed that energy storage costs are the same. The main costs are operating costs due to power conversion losses and capital costs of initial hardware including wires, power conditioning units, converters, and other extra costs. The following parameters are used in the model (see Table 10):

A detailed cost analysis is done in Opiyo (2019). Briefly, the levelized cost of electricity from of each minigrid is given by

$$LUCE = \frac{ALCC}{kW_p \times EHFS \times 365 \times CUF} \tag{8}$$

where kW_p is the rated peak kilowatt capacity of the minigrid, *EHFS* is the equivalent hours of full sunshine per day, *CUF* is the capacity utilization factor which incorporates non-utilization and

Table 10
Parameters used in the model.

Parameter	Value and unit	Description
$LUCE$	–	Levelised cost of electricity
$ALCC$	–	Annualized lifecycle cost
kW_p	400 kWp	Rated capacity of each minigrid
$EHFS$	8 h	Equivalent hours of full sunshine per day
CUF	0.9	Capacity utilization factor
C_{PV}	\$1400/kWp	Capital cost of the PV array
C_{batt}	\$0.95/Ah	Capital cost of the battery
C_{cpu}	\$2850	Capital cost of power conditioning unit
$C_{O\&M}$	\$2500/year	Operations and maintenance cost
i	12%	Discount rate
CRF_{pcu}	0.2774	Capital recovery factor of the power conditioning unit
CRF_{PV}	0.1339	Capital recovery factor of PV array
CRF_{batt}	0.2774	Capital recovery factor of the battery
C_{dn}	\$2500/km	Capital cost of the power distribution network
C_{sc}	\$125/consumer	Capital cost of service connections including internal wiring and appliances
L	1 km	Length of the distribution network
CRF_{pdn}	0.1770	Capital recovery factor of the distribution network
R	\$1400/kWp	Benchmark unit cost of the communal grid
b	0.95	Scale factor for incorporating cost reduction in overall cost of the minigrid
n	–	Life of particular component

outages of systems due to various reasons, and $ALCC$ is the annualized lifecycle cost which is calculated by summing up the cost of all of its individual components, i.e. the array, battery, power conditioning units (power electronics), and appliances multiplied by their respective capital recovery factors plus operations and maintenance costs. It is expressed as

$$ALCC = (C_{PV} \times CRF_{PV}) + (C_{batt} \times CRF_{batt}) + \left(C_{pcu} \times CRF_{cpu}\right) + [C_{PV} \times R]^{b} + [(C_{dn} \times L) + (C_{sc} \times N)] \times CRF_{pdn} + C_{O\&M} \tag{9}$$

where C_{PV} is the capital cost of the PV array, C_{batt} is the capital cost of the battery, C_{pcu} is the capital cost of the power conditioning unit, and R is the benchmark unit cost of a minigrid, b is a scale factor for incorporating cost reduction in overall cost of the minigrid, without the power distribution network (pdn), due to bulk purchasing of the components used in the grid. Its effect is uniformly distributed over all components of the communal grid, minus the distribution network. C_{dn} is the capital cost of the power distribution network per km, C_{sc} is the capital cost of service connections including internal wiring and appliances per consumer serviced, L is the length of the distribution network in km, and CRF_{pdn} is the capital recovery factor of the distribution network including the service connections. CRF_{PV}, CRF_{batt}, and CRF_{cpu} are the capital recovery factors of the PV array, the battery, and the power conditioning unit, respectively, while $C_{O\&M}$ is the operations and maintenance cost. It includes costs due to power losses in transmission and conversion stages as expressed in Eqs. (1)–(6).

Capital recovery factor (CRF) is calculated using the formula

$$CRF = \frac{i\,(1+i)^{n}}{(1+i)^{n} - 1} \tag{10}$$

where i is the discount rate while n is the life of the particular component being considered.

The required battery capacity for each string/array is given by

$$Batt(Ah) = \left(\frac{P \times h}{\eta_{inv(PV)} \times V \times MDoD \times \eta_{batt(PV)} \times DF}\right) \times D \tag{11}$$

where P is the power load, h is the number of hours the load is operated per day, V is the operating voltage of the battery, $\eta_{inv(PV)}$ is the efficiency of inverter, $MDoD$ is the maximum depth of battery discharge, $\eta_{batt(PV)}$ is the charging/discharging efficiency of the battery, D is the days of autonomy, and DF is the diversity factor, ratio of the sum of all individual peak loads to the maximum load of the entire minigrid.

(a) DC-coupled minigrid with decentralized storage

In these systems generated DC voltage by the PV systems is distributed throughout the minigrid in the DC form. Each DC–DC converter for each PV system is necessary for maximum power point tracking (MPPT) and for charge controlling of the storage system. The DC–DC converter also regulates and conditions the DC bus voltage. Fig. 3 shows a Simulink model used to implement a DC-coupled minigrid with decentralized. Each array consists of 66 parallel strings, each comprising 5 PV 330 SunPower (SPR-305-WHT-D) modules connected in series ($66 \times 5 \times 305.2 = 100.7$ kW). Each array is connected to a 5 kHz boost DC–DC converter with maximum power point tracking (MPPT) and charge-controlling capabilities. Each converter uses the perturb-and-observe method to extract maximum voltage (273 V DC) from each array and then boosts it to 500 V DC. Each Converter is connected to a decentralized lead acid battery bank rated at 1040 Ah, with a 25% depth of discharge (DOD), and 2 days of autonomy. The battery is then connected to a 500 V DC common bus. The load across each converter is stochastically allocated between 10 kW and 25 kW, based on Kendu Bay data and potential number of households served by each array (Opiyo, 2016, 2015) (see Fig. 2).

(b) DC-coupled minigrid with centralized storage

Each DC–DC converter for each PV system is still necessary for maximum power point tracking, however, the task of charge controlling is now performed by an appropriately sized central converter connected to the central storage system. Fig. 3 shows a Simulink model used to implement a DC-coupled minigrid with centralized storage. These systems are similar to DC-coupled systems with decentralized storage, with the exception being that the storage system is now centralized.

(c) AC-coupled minigrid with decentralized storage:

In these systems generated DC voltage by the PV systems are first inverted into AC form before being distributed throughout the network. Due to decentralized storage, each consumer has its own DC–AC inverter for connection to the common AC bus. A decentralized control system is used to set the network voltage amplitude and frequency. The system works by using a virtual communication system to independently determine the operating points of each decentralized PV system and load within the minigrid network, effectively eliminating the need for communication links and thus increasing system reliability as well as reducing cost (Bidram and Davoudi, 2012). This enables easy and cost-effective expansion of the minigrid by enabling decentralized PV systems and loads to have plug-and-play capabilities (Bidram and Davoudi, 2012). Every decentralized PV system, including the master has a built-in generation profile determined by P–f and Q–V droop curves. Each unit therefore determines its own real and reactive power, eliminating the need for communication networks in the process. The master VSI sets the voltage and frequency based on its droop and the PQ inverters determine the active power from the system frequency set by the master VSI and the reactive power from the local voltage measurements (Baert and Vervaet, 1999). Fig. 4 shows a Simulink model used to implement the minigrid; the DC–DC converter is connected to a 1980-Hz three-phase three-level DC–AC inverter through a DC link capacitor. The inverter inverts the 500 V DC to 260 V AC, while keeping a unity power factor. It uses two control loops: one which regulates DC link voltage to +/−250 V and an internal control loop which regulate active and reactive current.

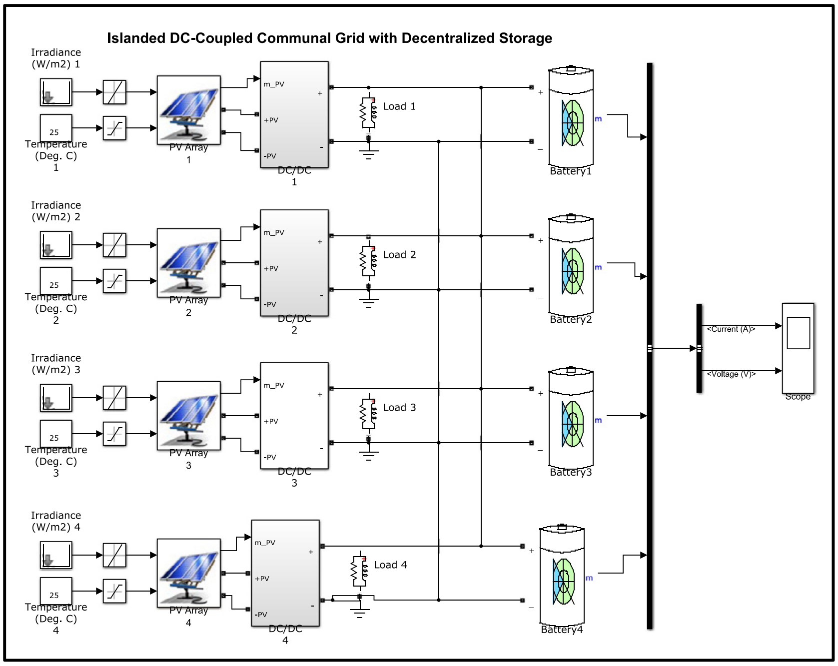

Fig. 2. Simulink model of islanded DC-coupled communal grid with decentralized storage.

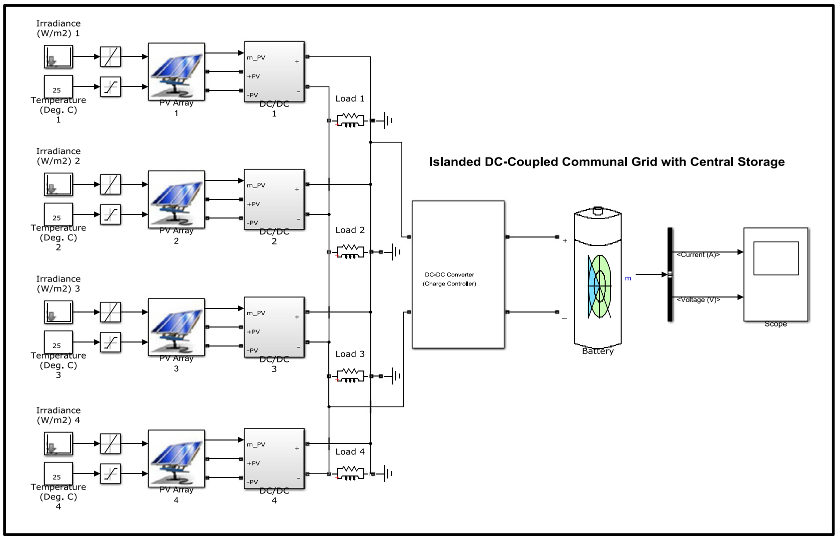

Fig. 3. Simulink model of islanded DC-coupled communal grid with centralized storage.

Active current reference is the output of the DC voltage external controller while reactive current reference is set to zero in order to maintain unity power factor.

(d) AC-coupled minigrid with centralized storage

In these systems, each consumer has its own PV system connected to a DC–DC converter for maximum power point tracking. The converter is then connected to a DC–AC converter for connecting to the common AC bus. A bi-directional AC–DC inverter with charge controlling capabilities is used to connect the central energy storage system to the common AC bus. Since the central inverter is large compared to the individual consumer inverters, it could act as master VSI for setting up reference line voltage amplitude and frequency while household inverters function as PQ inverters. Fig. 5 shows a Simulink model used to implement the network. Here each DC–DC converter extract maximum power from the PV array and then boosts it to 500 V DC. Each converter is connected to a DC–AC inverter which then inverters the 500 V DC to 260 V AC and then feeds it to the common bus. Each DC–DC converter is also connected to a central storage system through a central DC–DC charge controller. Future connections to the minigrid are complicated by the fact that each time the storage capacity is increased to meet the increased demand; a new appropriately sized AC–DC inverter must be purchased for the network. Putting such a cost on the new consumer would dissuade potential consumers from joining the minigrid.

4. Results and discussion

Minigrids architectures and operation modes determine initial investment costs, operations and maintenance costs, and future expansion possibilities. Energy storage systems are needed for stability of power supply in case of islanded operations. To achieve this, power electronics are needed for operational control and network interfacing. In this section we model islanded

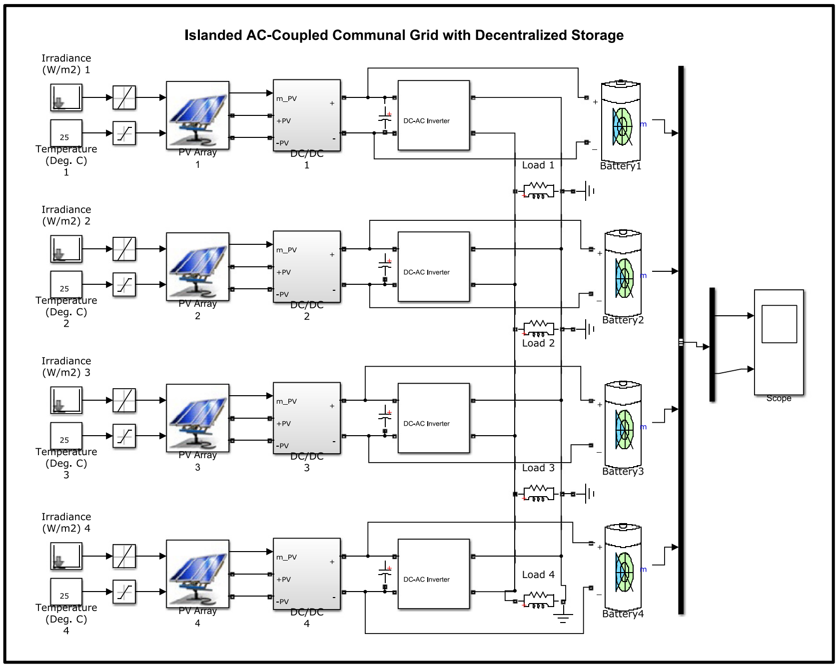

Fig. 4. Simulink model of islanded AC-coupled communal grid with decentralized storage.

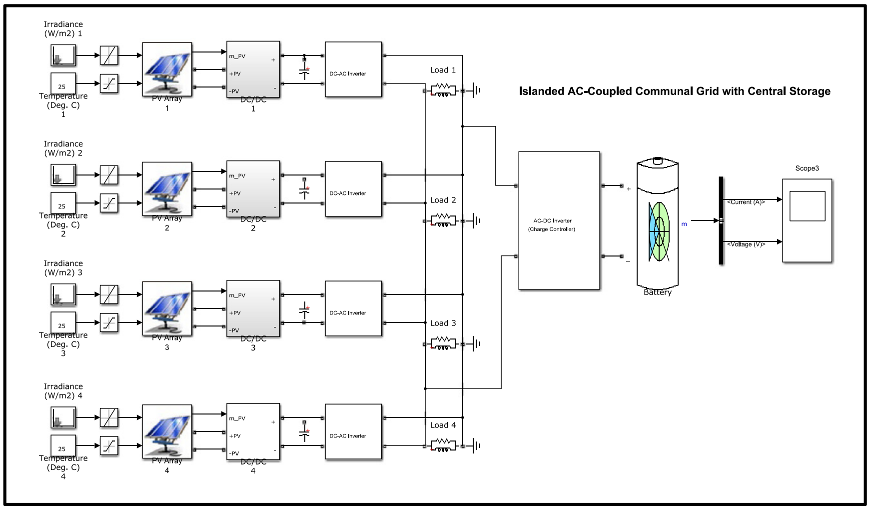

Fig. 5. Simulink model of islanded AC-coupled communal grid with centralized storage.

minigrids with either centralized or decentralized storage in DC-coupled or AC-coupled networks to compare costs of such networks due to avoided conversion stages. Each of the PV arrays simulated has 4 PV arrays, each rate at 100 kW at 1000 W/m^2 radiation and 25 °C. Fig. 6 shows a comparison of irradiances hitting the 4 PV arrays shown in all simulations within 3 s (duration of simulation), while Fig. 7 shows the voltages produced by each of the 4 PV arrays as a result of the irradiances; each array is connected to a DC–DC boost converter with maximum power point tracking (MPPT) capabilities, keeping the average voltage at about 250 V for each array. The blips in the figure correspond to points of changes in irradiances. The maximum voltage produced by each array at any given time is 273 V. This is then boosted to 500 DC by the converters for the common bus.

Fig. 8 shows the power output from the 4 PV arrays. Power output mirrors the irradiance hitting the arrays. The four power outputs from the PV arrays sum up to active power injected into the control inverter as shown in Fig. 9. As discussed above, reactive power is kept at zero to ensure unity power factor.

Table 11 shows a comparison of additional power electronics required for different layouts. From the table it is clear that in islanded modes, DC-coupled networks with decentralized storage are the cheapest options for rural developing communities, with no additional costs beyond costs common to all other minigrid architectures. These are followed by DC-coupled networks with centralized storage which required additional investments in centralized charge controllers. AC-coupled networks with decentralized storage which need 4 DC–AC inverters come in third, followed by AC-coupled networks with centralized storage which need a central charge controller in addition to the 4 DC–AC inverters.

Fig. 10 shows a comparison of consumers connected to minigrids in decentralized and in centralized storage configurations while Fig. 11 shows their corresponding percentages. It is assumed that the total storage capacities in both centralized and

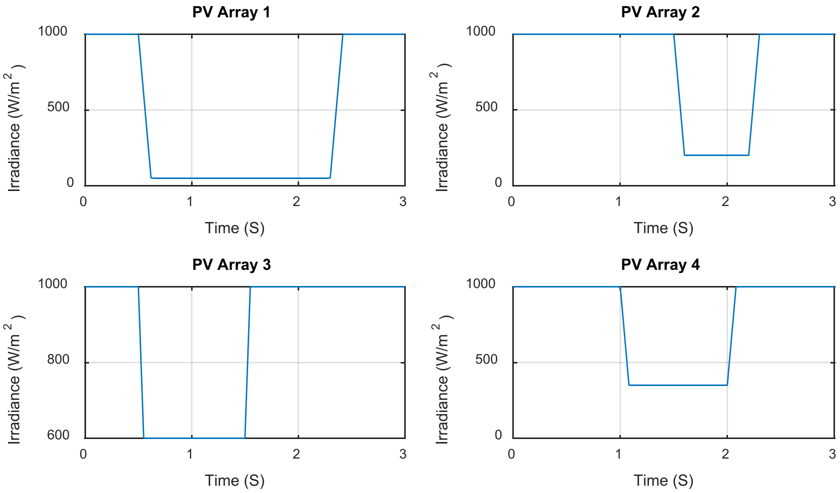

Fig. 6. Mean irradiances hitting the PV arrays.

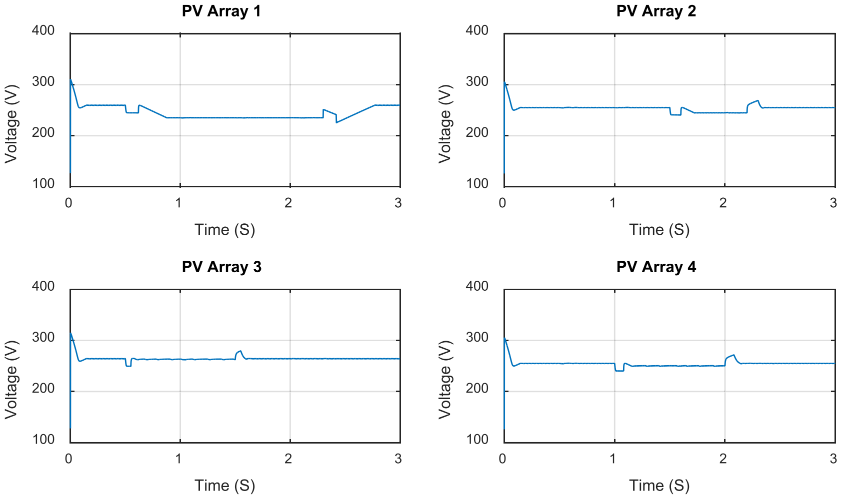

Fig. 7. Mean voltages produced by the PV arrays.

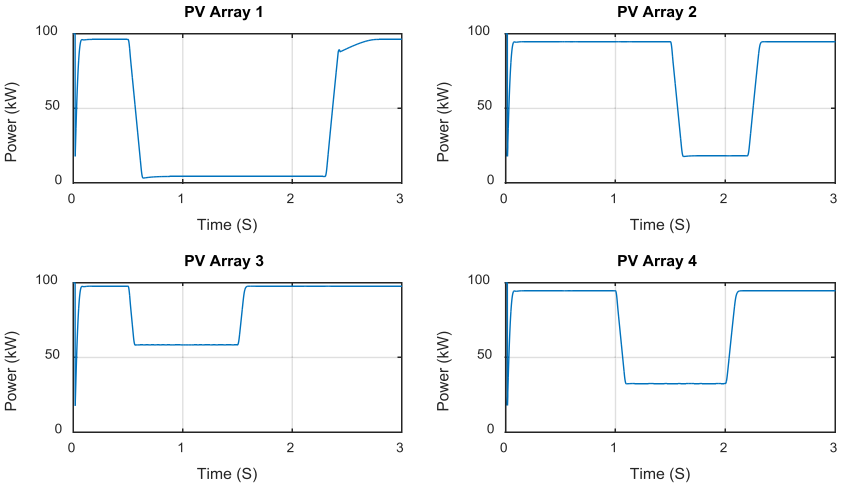

Fig. 8. Mean power outputs from the PV arrays.

decentralized systems are the same and that the total investment costs in both are also equal. The determining factor in what choice of a minigrid to join is therefore the additional cost brought about by the central charge controller (additional conversion stage) and the ease of joining or leaving a particular minigrid architecture, i.e., ease of its expansion. In the simulations, the total number of households are increased annually as per national population growth rate, and based on the most recent census. After 25 years,

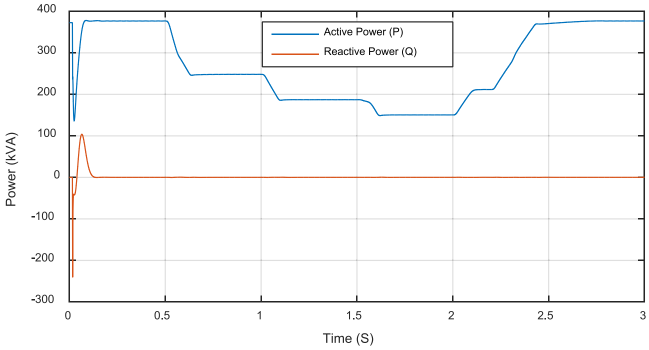

Fig. 9. Active and reactive power.

Table 11
Comparison of additional power electronics required by different minigrid networks.

Additional power electronics	Islanded			
	Centralized storage		Decentralized storage	
	DC	AC	DC	AC
VSI	0	0	0	0
Central charge controller	1	1	0	0
DC–AC inverter	0	4	0	4
DC–DC inverter	4	4	4	4

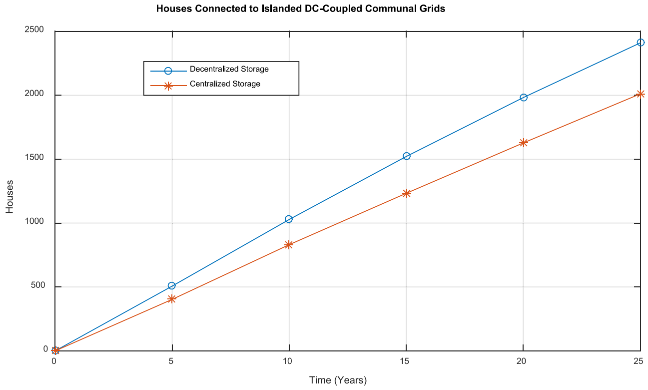

Fig. 10. Consumers connected to islanded DC-coupled networks.

2410 consumers would have joined minigrids with decentralized storage systems, representing 24.6% of all households. This is slightly higher than the 2011 households that would have joined networks with centralized storage systems, representing 20.5% of all households. It is clear that the additional investment cost required for centralized storage drive more consumers towards networks with decentralized storage.

Fig. 12 shows a comparison of consumers connected to minigrids in decentralized and centralized storage configurations, while Fig. 13 shows their corresponding percentages. In addition to investments costs incurred with similar DC-coupled networks, AC-coupled networks also require DC–AC inverters for each PV array for common bus interfacing. Here also it is assumed that the total storage capacities in both centralized and decentralized systems are the same and that the total investment costs in both are also equal. After 25 years, 2179 consumers would have joined minigrids with decentralized storage systems, representing 22.2% of all consumers. This is higher than the 1728 consumers that would have joined networks with centralized storage systems, representing 17.6% of all consumers.

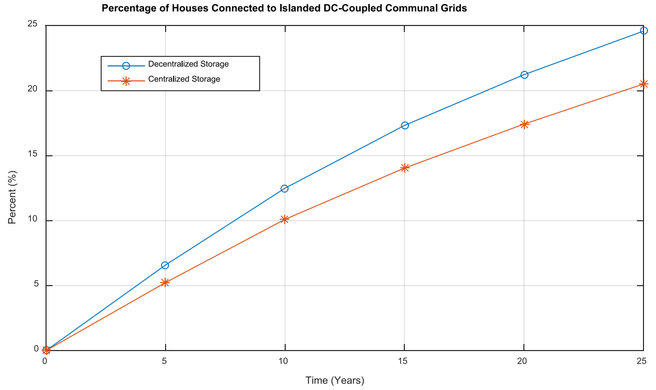

Fig. 11. Percentage of consumers connected to islanded DC-coupled networks.

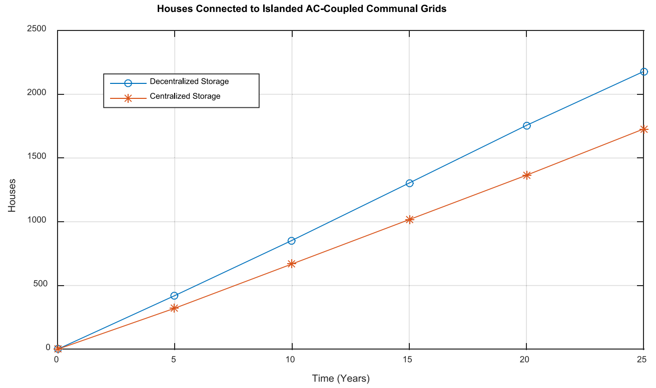

Fig. 12. Consumers connected to islanded AC-coupled networks.

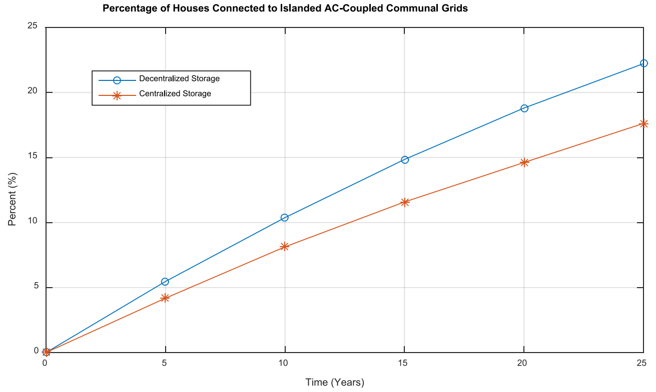

Fig. 13. Percentage of consumers connected to islanded AC-coupled networks.

Table 12 shows a comparison of consumers connected to various islanded minigrids after 25 years. It is clear from the table that more consumers will have joined networks with decentralized storage systems, whether they be DC- or AC-coupled. In the same category, i.e. decentralized or centralized storage, more consumers would join DC-coupled networks than AC-coupled networks. This is due to additional costs incurred in DC–AC inverter purchases, and due to low efficiencies of such systems due to more power loss points.

5. Conclusions

In this work DC versus AC power systems are explored as cost-effective options for rural electrification in sub-Saharan Africa.

Table 12
Comparison of consumers connected to minigrids under different islanded architectures.

Time (years)	DC-coupled		AC-coupled	
	Decentralized storage	Centralized storage	Decentralized storage	Centralized storage
0	0	0	0	0
5	507	403	421	322
10	1028	831	854	669
15	1521	1233	1304	1017
20	1982	1627	1756	1365
25	2410	2011	2179	1728

Minigrids bridge the gap between small solar home systems with limited power capacity and the national utility grid, which is often unavailable and unreliable in rural developing sub-Saharan Africa. They provide electricity beyond lighting for produce use, and thus stimulate rural socio-economic developments. In this work, we have compared DC versus AC minigrids in terms of costs, efficiency, and feasibility in rural electrification. Research shows that power losses in distribution networks, and conversion losses at different stages are the biggest losses in minigrids, and form the biggest parts of their operating costs. By avoiding many power conversion stages, DC networks supplied by DC power sources such as PV systems are the most cost-effective paths to rural electrification. Efficiencies could be improved further if DC-inherent appliances are used with the DC networks, further eliminating power conversion losses. Results also show that, based on costs, consumers would prefer to join DC minigrids as opposed to AC minigrids due to lower connection fees, ease of grid expansion, and overall better performances.

References

Baert, D., Vervaet, A., 1999. Lead–acid battery model for the derivation of Peukert's law. Electrochim. Acta 44 (20).

Bidram, A., Davoudi, A., 2012. Hierarchical structure of microgrids control system. IEEE Trans. Smart Grid 3, 1963–1976.

Chaurey, A., Kandpal, T., 2010. A techno-economic comparison of rural electrification based on solar home systems and PV microgrids. Energy Policy 38, 3118–3129.

Eerge Alliance, http://www.emergealliance.org/.

Garbesi, K., Vossos, V., Shen, H., 2011. Catalog of DC Appliances and Power Systems. Lawrence Berkeley National Laboratory, Berkeley, CA, LBNL-5364E.

Hammerstrom, D., 2007. AC versus DC Distribution systems - Did we get it right?. In: Power Engineering Society General Meeting. IEEE, pp. 1–5.

http://en.wikipedia.org/wiki/Induction_cooking.

http://appliances.energy.ca.gov/quicksearch.aspx.

International Energy Agency (IEA), World Energy Outlook, 2018.

International Energy Agency (IEA), World Energy Outlook, 2016.

Laudani, G., Mitcheson, P., 2017. Comparison of Cost and Efficiency of DC versus AC in Office Buildings, Report for Transformation of the Top and Trail of Energy Networks. Imperial College, London.

Lawrence Berkeley National Laboratory, What the Real World Tells Us About Saving Energy in Electronic, https://eta.lbl.gov/ea/nordman/docs/e3s_nordman.pdf.

Lighting Global, Off-Grid Solar Market Trends Report, 2016.

Mohan, N., 2012. Power Electronics - A First Course. John Wiley & Sons, Inc.

Opiyo, N., 2015. Modelling pv-based communal grids potential for rural western kenya. Sustainable Energy Grids Netw. 4, 54–61.

Opiyo, N., 2016. A survey informed pv-based cost-effective electrification options for rural sub-saharan africa. Energy Policy 91, 1–11.

Opiyo, N.N., 2018a. Different storage-focused PV-based mini-grid architectures for rural developing communities. Sustainable Energy Grids Netw. 9 (5), 75–99.

Opiyo, N.N., 2018b. Droop control methods for PV-based minigrids with different line resistances and impedances. Sustainable Energy Grids Netw. 9 (6), 101–112.

Opiyo, N.N., 2019. Impacts of neighbourhood influence on social acceptance of small solar home systems in rural western kenya. Energy Res. Soc. Sci. 52C, 91–98.

Techakittiroj, K., Wongpaibool, V., 2009. Co-existence between AC-distribution and DC-distribution: in the view of appliances. In: Second International Conference on Computer and Electrical Engineering. ICCEE.

Vallve, X., Serrasolses, J., 1997. Design and operation of a 50 kWp PV rural electrification project for remote sites in spain. Sol. Energy 59, 111–119.

Vossos, V., Johnson, K., Kloss, M., et al., 2017a. A Market Assessment for DC Distribution Systems in Buildings. Lawrence Berkeley National Laboratory, Berkeley, CA.

Vossos, V., Pantano, S., Heard, R., et al., 2017b. DC Appliances and DC power distribution. In: A Bridge to the Future Net Zero Energy Homes. Lawrence Berkeley National Laboratory (LBNL).