SMART VILLAGES
New thinking for off-grid communities worldwide

The future of direct current electrical systems for the off-grid environment

Grant Kopec, Michael Price, John Holmes

Technical report 8

December 2016

Key words:
Alternating current, Direct current, Micro-grid, Mini-grid, Nano-grid, Electrical systems, Off-grid energy

Smart Villages

We aim to provide policymakers, donors, and development agencies concerned with rural energy access with new insights on the real barriers to energy access in villages in developing countries—technological, financial and political—and how they can be overcome. We have chosen to focus on remote off-grid villages, where local solutions (home- or institution-based systems and mini-grids) are both more realistic and cheaper than national grid extension. Our concern is to ensure that energy access results in development and the creation of "smart villages" in which many of the benefits of life in modern societies are available to rural communities.

www.e4sv.org | info@e4sv.org | @e4SmartVillages

CMEDT - Smart Villages Initiative, c/o Trinity College,
Cambridge, CB2 1TQ

Publishing

The Smart Villages Initiative is being funded by the Cambridge Malaysian Education and Development Trust (CMEDT) and the Malaysian Commonwealth Studies Centre (MCSC) and through a grant from the Templeton World Charity Foundation (TWCF). The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the Cambridge Malaysian Education and Development Trust or the Templeton World Charity Foundation.

MALAYSIAN COMMONWEALTH
STUDIES CENTRE
CAMBRIDGE MALAYSIAN
EDUCATION AND DEVELOPMENT
TRUST

TEMPLETON
World Charity Foundation, Inc.

CONTENTS

EXECUTIVE SUMMARY

Rural areas that are not connected to an electricity grid are nevertheless seeking to increase their use of electricity to support services such as healthcare, education, and entertainment, and for productive uses to increase incomes. Such increases in electricity use in rural communities—“climbing the energy ladder”—require a step-change in electricity provision to currently off-grid households.

The supply of electricity through centralised generation and a long-distance grid generally uses alternating current, or AC, for distribution to households and buildings. However, this report demonstrates that many of the electrical technologies upon which appliances are based are powered by direct current (DC) electricity.[1] The technologies that supply electricity for off-grid settlements (in particular solar photovoltaic panels and batteries) often generate DC electricity as well. Micro-grids that integrate DC-native electricity supplies with DC distribution and DC-native electrical appliances may possess energy efficiency and cost advantages over the AC distribution systems used on the main grid today because of the lack of a need for energy conversion from AC to DC.

However, there are three barriers to the widespread adoption of integrated DC generation, distribution, and appliance systems:

1. The local context will determine the design of the micro-grid, which will in turn determine whether it is advantageous to have a DC or AC architecture.
2. The availability of DC appliances and electrical equipment lags far behind their AC counterparts, and the capital costs are consequently larger.
3. The standards, regulation, and expertise for the design and installation of DC micro-grids lags far behind that of comparable AC systems.

The proliferation of solar home systems and single appliances that contain their own PV power supply, most commonly pico-solar lights, has the potential to drive an implementation of DC devices at a mass scale. However, under the wrong conditions, they also have the potential to reduce impetus for the installation of larger DC micro-grids, as many are not currently standardised and are therefore less capable of easy integration in local DC grids.

---

[1] *Technologies that generate or run on DC electricity without the need for converting the current to or from alternating current are called ‘native DC’ technologies.*

INTRODUCTION

One of the United Nations' Sustainable Development Goals is "universal access to affordable, reliable, and modern energy services".[2] Electricity, as a clean, high quality "fuel", is generally regarded as being at the top of the energy ladder of fuel sources (Van Der Kroon et al. 2013). In regions with mature infrastructure, access to electricity has traditionally been provided through centralised generation combined with an electricity grid. The electricity grid is one of the oldest pieces of technology and infrastructure. Its alternating current (AC) format was settled in the "current wars" of the late nineteenth century, and this general structure has survived, largely intact, into modern times.

However, the demand for electricity within regions without a mature or reliable electricity distribution grid is increasing faster than grid connections in these regions can be constructed. This shortage of grid-supplied electricity, combined with new technologies such as solar photovoltaics which enable clean, local, direct current (DC) generation of electricity, has presented those communities with a choice to construct either traditional AC electrical systems, or to invest in DC distribution and appliances.

Electrical appliances that run on direct current have historically been restricted to mobile applications because of their capacity to run on battery power without a conversion to alternating current. With the increased efficiency and decreased price per watt for distributed energy generation systems, in particular solar photovoltaics, the combination of distributed energy systems, DC electricity distribution, and DC appliances has become feasible for off-grid homes, villages, and installations. While the supply, transformation, distribution, and appliance technologies exist to make off-grid DC systems feasible, the extent to which they will be adopted for off-grid use in the next 20 years is unknown. This report examines the technological, economic, and practical choices, and the barriers to the widespread adoption of integrated DC electricity supply, distribution, and use systems at the local scale.

The increase in energy use and the evolution of fuel choice among households, farms, and small businesses in developing regions has been extensively studied, as reviewed by Van Der Kroon et al. (2013). While electricity is generally considered to be the most desirable fuel, such studies generally do not differentiate between AC or DC electricity. As this report will demonstrate, the choice between an AC or DC electricity infrastructure for off-grid applications is one with as much complexity as the choice between, say, wood fuel, gas fuel, or electricity for heating.

---

[2] *http://www.un.org/sustainabledevelopment/energy/*

REVIEW OF AC AND DC ELECTRICAL SYSTEM COMPONENTS

The choice between AC and DC for off-grid electricity systems starts with an understanding of the differences between these two electricity waveforms, and the conversion technologies to transition between them. Next, the supply, distribution, and demand technologies which constitute off-grid electricity systems can be put into context.

1.1 Electricity conversion technologies

Alternating current (AC) electricity has a varying voltage, while direct current (DC) has a constant voltage. Typically, electricity with an AC waveform alternates between positive and negative voltages, meaning that the current switches direction when the voltage changes its sign. An AC waveform where the negative voltages have been changed to positive voltages is said to have been rectified. Figure 1 shows illustrative AC, rectified AC, and DC waveforms.

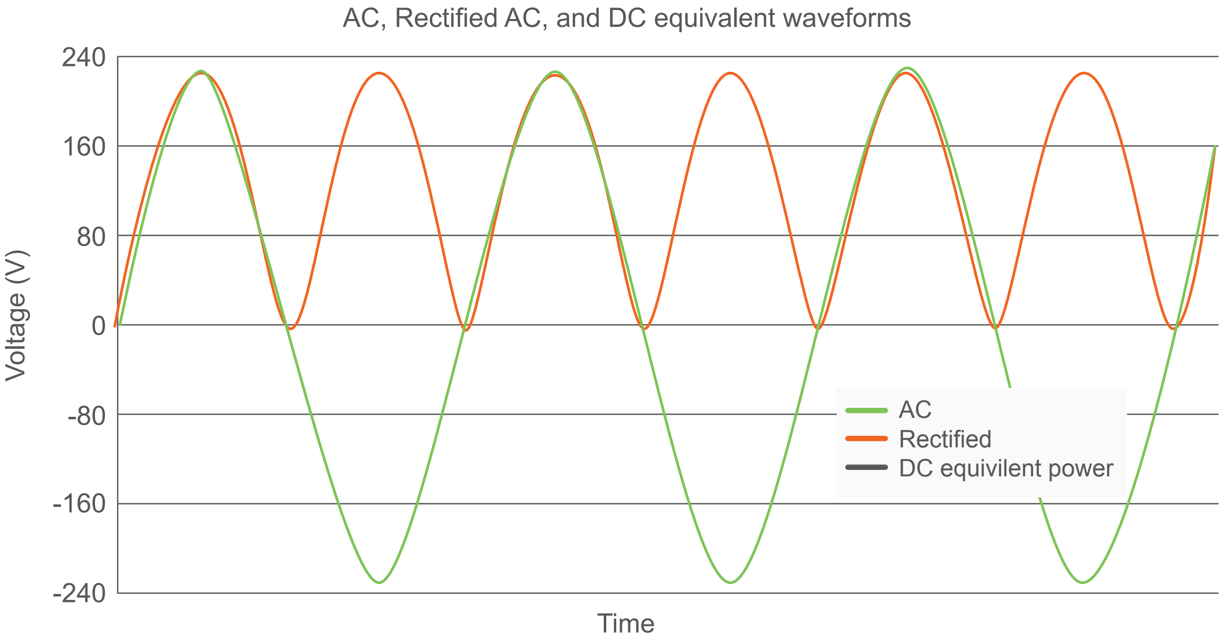


Figure 1: Illustrative AC, rectified AC, and DC waveforms, all of which have the same root-mean-squared (RMS) voltage[3] and the same electrical power.

Differing requirements for electricity generation, distribution, and use mean that electricity must be converted between different waveforms and voltages. In general, electrical conversions are more energy and cost efficient at larger scales. In contrast, many electricity using devices contain internal power converters, which are relatively energy inefficient as well as more expensive per unit of power converted.

1.1.1. AC to DC technology

Converting from alternating current to direct current requires a rectifier, which transforms the negative portion of the AC waveform to a positive

---

[3] The root mean squared voltage is the effective voltage of an AC waveform. An AC waveform will deliver the same amount of power, on average, as a DC current with the same voltage as the AC root mean squared voltage.

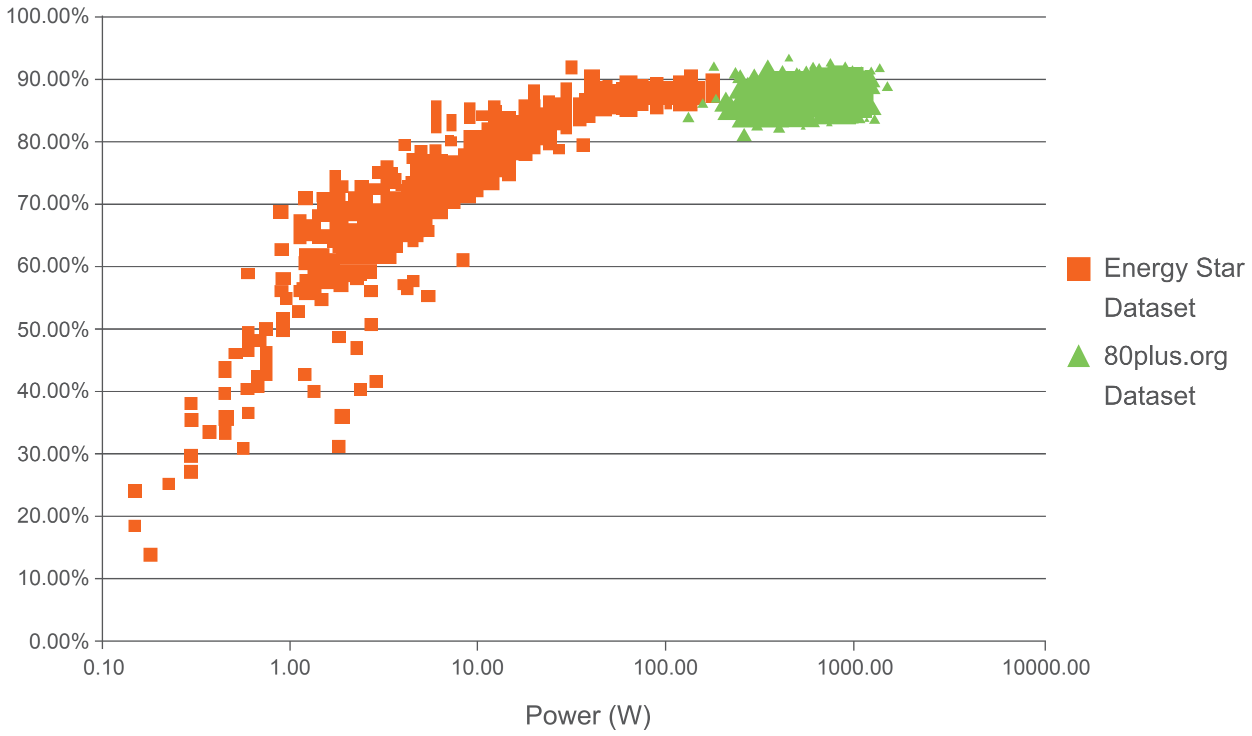


Figure 2: AC-DC conversion efficiencies within DC-native appliances with an AC electricity input (Garbesi et al. 2011).

voltage. A rectified AC waveform will still have a varying voltage, but that voltage will always be a unipolar voltage[4], and therefore the current flow will flow in one direction, as seen in Figure 1. The rectified AC waveform can then be smoothed to a DC waveform using a capacitor.

The conversion of an AC waveform to DC is not 100% efficient. For example, the theoretical maximum efficiency of an analogue full-wave rectifier is 81%. However, modern digital power conversion electronics allow AC to DC conversion efficiencies to be between 90 and 99% (Kolar and Miniböck 2012). The efficiency of this conversion is dependent on both the design of the converter and the amount of electrical energy that is being converted relative to the size of the converter, as demonstrated in Figure 2.

1.1.2. DC to AC technology

Converting from direct current to alternating current requires an inverter. Historically, inverters were constructed from mechanical components. Modern inverters are composed of electronics. Inverters can produce AC output as square waves, sine waves, or intermediate wave forms in between, as seen in Figure 3.

The peak efficiency of a typical modern power electronic inverter sized for off-grid use is 92-96%, which will occur at approximately 25% of the maximum rated power (Perez 2006). Vignola et al. also find that modern inverter efficiency in a real-world system is 90-95% (2008). As seen in Figure 4, the efficiency penalty for operating above the maximum efficiency point is small, while inverters can be very inefficient at low power.

---

[4] *A unipolar voltage is one with a consistent sign, either positive or negative.*

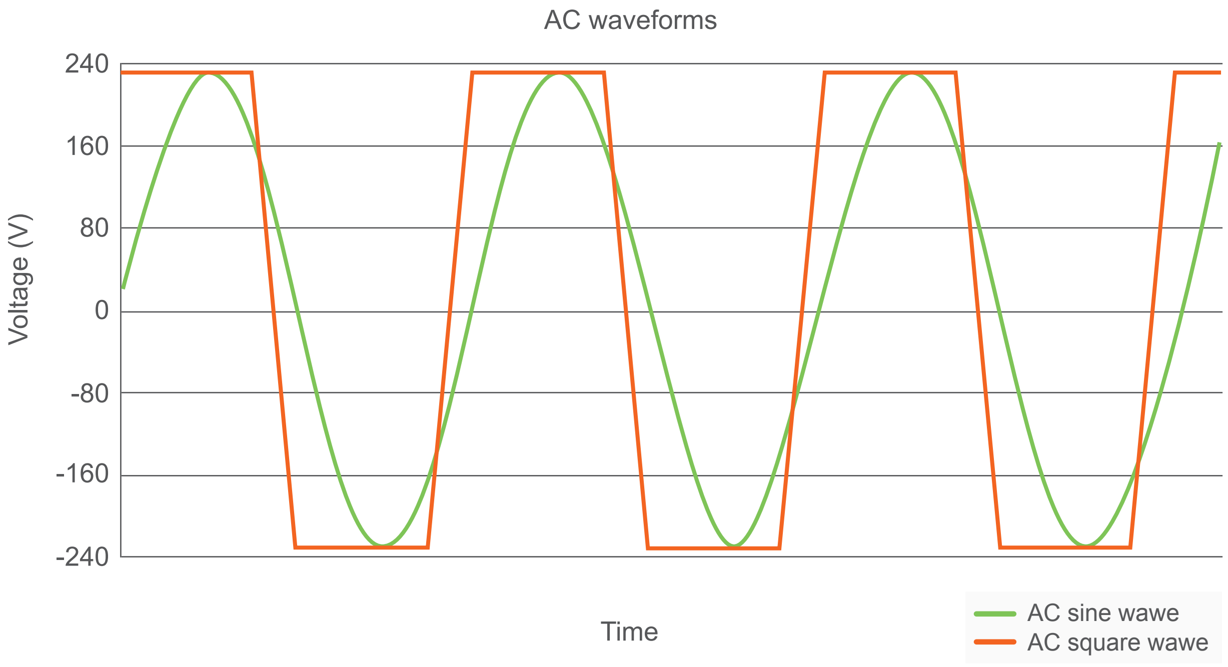


Figure 3: Alternating current with a sine-wave waveform and a square-wave waveform.

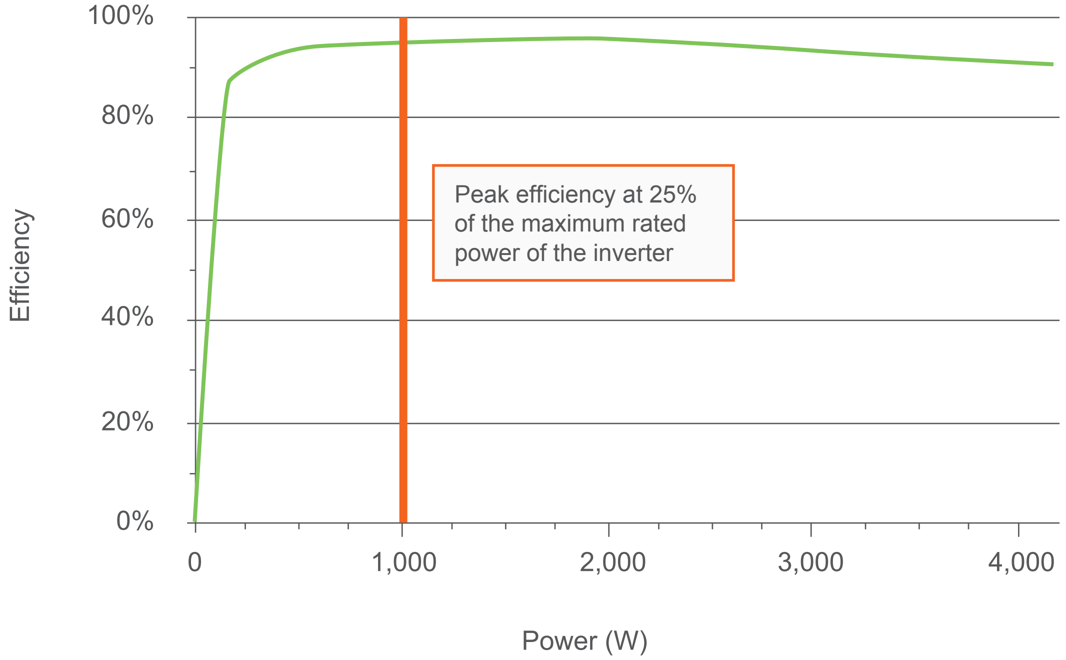


Figure 4: Typical efficiency vs. power curve for a power electronics DC to AC inverter with a 4,000 W rating (Perez 2006).

The construction of small and efficient inverters is an area of active research. In 2014, for example, Google and the Institute of Electrical and Electronics Engineers (IEEE) sponsored a contest to shrink the size of inverters for households (rated at approximately 5 kW) from their typical size of around 1 m^3 by a factor of 10.[5]

1.1.3. DC to DC technology

The efficient conversion between DC voltages is important if DC distribution continues to gain in popularity, because the optimum voltage for distribution of DC electricity throughout a dwelling and between dwellings depends on both energy efficiency and safety considerations. Furthermore, efficient DC-DC conversion may be needed for appliances operating at a different DC voltage than the mains voltage. Converting from an input DC voltage to a different output DC voltage has an efficiency between 90 and 98% (Oliver 2012)[6]. DC-DC voltage conversion used to be difficult, but switch mode digital technology has steadily improved the efficiency of this type of conversion, and the implementation of wide band-gap semiconductors should increase DC-DC conversion efficiency even further.[7]

1.1.4. AC to AC technology

An AC waveform may be converted to another AC waveform of different voltage, current, or shape. This conversion can be made with three general types of converter: a DC-link converter, cycloconverter, or matrix converter.

A DC-link converter converts an AC waveform to DC, and then to another AC waveform. Thus, AC electricity generation technologies such as wind turbines, micro hydro power, and diesel generators already have energy efficiency losses because of the need to perform an AC-AC conversion to match their voltage, frequency, and phase with that of the AC distribution grid. If using a DC-link converter, the AC output of these generators is converted to DC electricity in an intermediate step before being converted into the desired AC waveform.

Cycloconverters convert an AC waveform to a lower frequency waveform without an intermediate DC conversion, but they are typically used only in large industrial applications.

Matrix converters are a new technology that also do not have intermediate DC conversion. They do not currently have large market penetration because of the high cost of high-quality semiconductor technology required for their construction. In the future, matrix converters could find a role in AC to AC conversion technology, though they are only appropriate for larger, poly-phase electrical systems.

1.1.5. Summary of conversion technologies

Electrical conversion technologies are a crucial determinant of the energy efficiency and efficacy of distributed energy generation coupled with micro-grids. The following general conclusions apply:

- Modern semiconductor power electronics have, in general, made the conversion of electricity into different forms much more efficient than with analogue converters. The energy efficiency of conversion is in most cases greater than 90%.

- However, high energy efficiency depends on operating within a converter’s “sweet spot”. Operating at electricity loads either greater than, or especially less than, the ideal range can have severe energy efficiency penalties. Thus, if a converter is sized to supply power to several high-energy appliances, then it will likely be very inefficient when supplying power for lighting only.

---

[5] *https://www.littleboxchallenge.com/*

[6] *http://electronicdesign.com/energy/dc-dc-converters-aim-efficiency*

[7] *http://spectrum.ieee.org/green-tech/buildings/dc-microgrids-and-the-virtues-of-local-electricity*

- The cost and efficiency metrics vary considerably as a function of the size and design of converter, with smaller-capacity converters being, in general, less energy efficient.

- Electricity conversion is an area of active research, with new developments in efficient, cheap, and small converters expected in the next ten years.

As will be demonstrated in this report, the need for multiple conversions between AC and DC forms of electricity is a significant determinant of the total energy efficiency of off-grid electricity systems.

1.2 Electricity supply technologies

Energy supply technologies that are suitable for off-grid applications either produce electricity directly from light, through photovoltaic panels, or they use another form of energy to drive an axially spinning generator. In this section, the form of power output of these supply technologies is reviewed.

1.2.1. Photovoltaic panels

Photovoltaic (PV) panels convert light energy into electrical energy. They produce a DC electrical output, where the current and resulting power are proportional to the intensity of the incident sunlight. The voltage of a single PV cell is approximately 0.5 V, and they can be wired in series to obtain the desired system voltage. PV panels are ideal for small off-grid applications, because they are scalable from very small sizes to very large sizes.

PV systems will produce variable voltage and current, and therefore power, depending on the amount of sunlight (the solar insolation and measured in watts per square metre). Figure 5 shows the variable power output of a solar panel as a function of the current produced. A maximum power point tracker (MPPT) is used to alter the load on the PV cells to produce the maximum power possible for a given voltage. The voltage where the cell produces its maximum power can then be converted with a DC-DC converter to the voltage that is used for the grid, appliance, or battery system. MPPTs have an efficiency of approximately 95%.

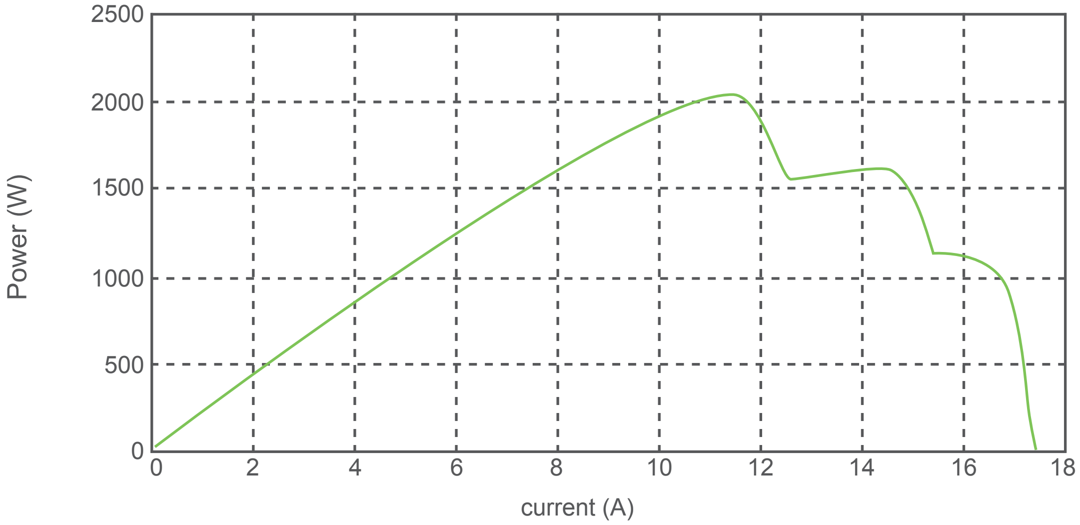


Figure 5: Power vs. current data for a solar panel which is non-uniformly insolated (the sunlight hitting the array is not constant over the area of the array). Figure from Carannante et al. 2009.

Solar systems can be wired in one of two basic configurations[8]. In the first, solar panels are connected together in a string, and the resulting high current DC electricity can be converted to AC through a large inverter, or to the appropriate DC voltage using a DC-DC converter. In this configuration, individual panels may or may not have MPPTs. In the second, each solar panel has a micro-inverter to convert that panels' output to higher voltage AC electricity, again either with or without an MPPT[9]. The requirements of the electricity supply system determines which of these configurations is preferable. The first configuration is typically used for DC system architectures. The second configuration may have lower overall efficiency losses[10] and may be more reliable because there is not a single point of failure at the large inverter.

1.2.2. Wind and water turbines

Wind or moving water can be used to drive turbines. Wind turbines are manufactured in sizes from 0.05 kW versions meant for mobile uses, to devices that can produce 8 MW or more. Similarly, micro water turbines have been manufactured that have a peak power production smaller than 1 kW. Both wind and water turbines produce electricity via an axially-spinning generator AC generator.

However, because of the variable speed of the fluid in which the turbine operates, as well as turbulence effects, the voltage, current, and frequency of the AC electricity output will not be constant. Therefore, these devices usually convert this variable-form AC electricity to DC electricity, which can then be converted back to an AC signal which is appropriate for either the main grid or an AC micro-grid, as seen in Figure 6.

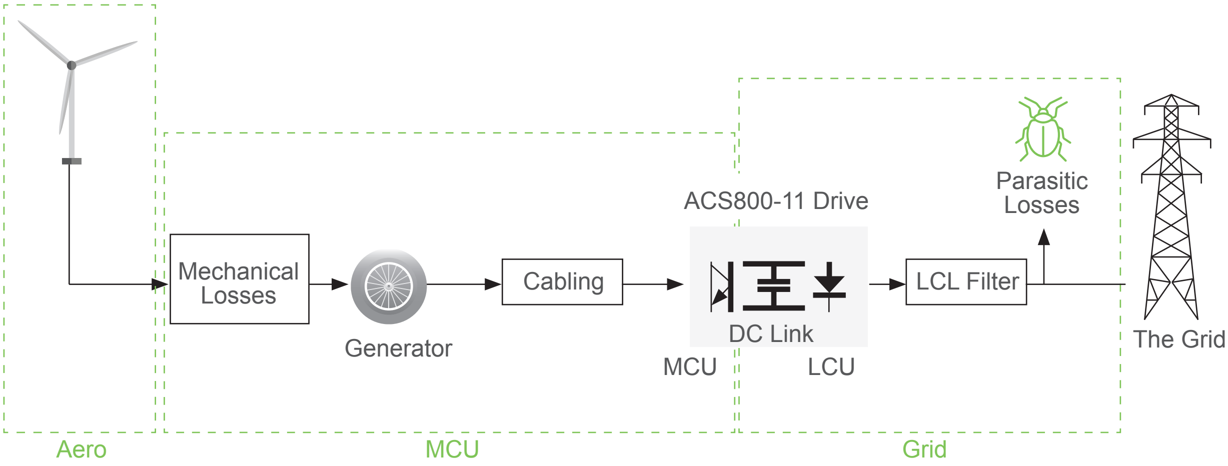


Figure 6: Energy conversion stages between an off-grid sized turbine (that in this case is still be connected to the grid) (The Quiet Revolution[11] QR5). There are losses at each stage: mechanical losses in the turbine, electrical losses in the motor control unit (MCU), which converts AC current to DC current; electrical losses in the local control unit, which converts the current back to AC; and electrical losses in the LCL filter, which smooths the AC signal and makes it appropriate for either direct use or input into the grid. Figure adapted from Bertényi and Young 2009.

---

[8] *http://electronicdesign.com/energy/don-t-judge-solar-pv-system-s-efficacy-inverter-efficiency-alone*

[9] *https://www.sdtc.ca/en/portfolio/projects/nano-inverter-chipset-development-and-demonstration-ac-bipv-architectures*

[10] *Due to lower resistive cable losses because current is transmitted as higher voltage AC rather than lower voltage DC.*

[11] *http://www.quietrevolution.com/*

There are losses at each stage of energy conversion. Figure 7 shows the combined efficiencies of the MCU (micro-controller unit) and grid blocks in Figure 6.

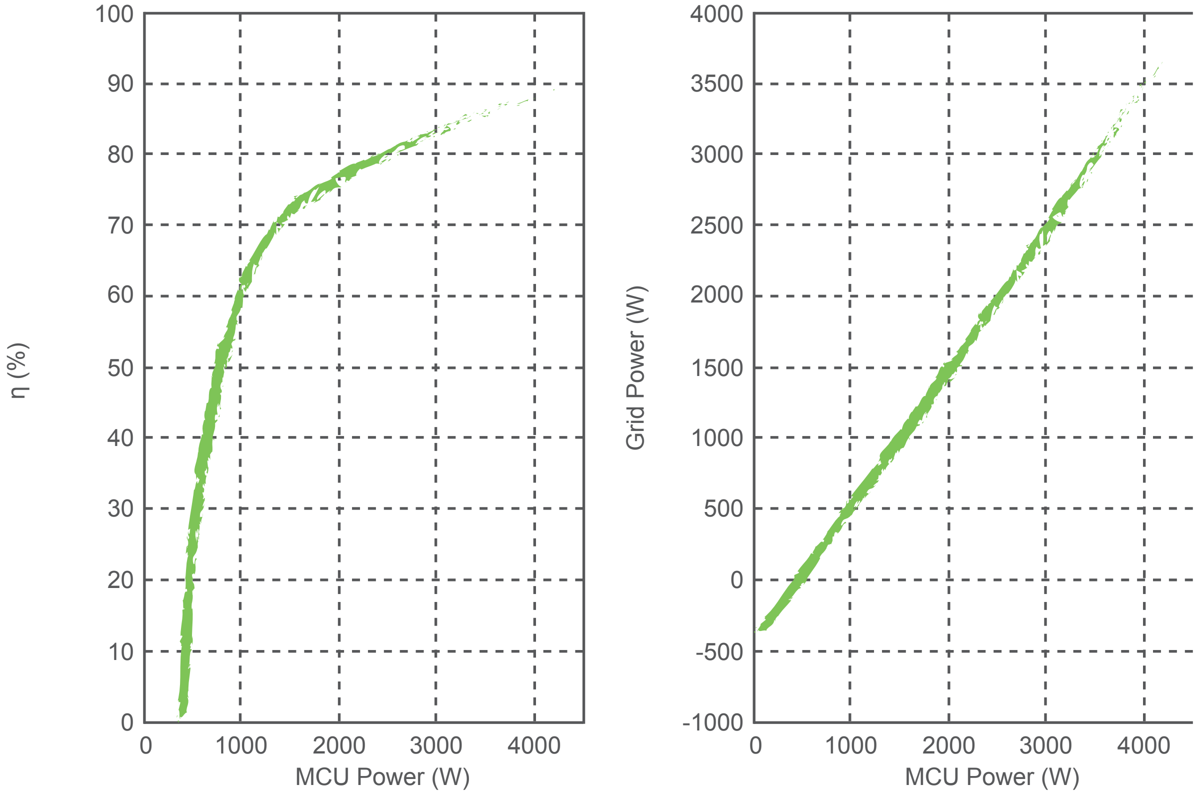


Figure 7: Combined efficiency of the MCU and grid blocks for the system in Figure 6. Efficiency is shown at left, while power-out vs. power-in is shown at right. Figure adapted from Bertényi and Young 2009.

While the data in Figure 7 are generated for a particular wind turbine, the general shape of the curve shows that (1) the efficiency of wind and water turbines drops off rapidly at low fluid speeds and/or high fluid turbulence; and (2) losses from the AC-DC-AC conversion as well as AC filtering are significant losses in this system. Therefore, these rotary electricity generation devices, even though they produce an AC output, may produce more net electricity when connected to a DC architecture, though this would be dependent on the efficiency of using a DC-DC converter compared to a DC-AC converter.

1.2.3. Internal combustion and steam generators

Internal combustion generators produce electricity through the combustion of a fuel; usually diesel, petrol, biomass, or natural gas. Similarly, steam-driven generators use high temperature water vapour to drive the generator. The steam used to drive these generators may be obtained from combustion of fossil fuels, a solar thermal power plant or a geothermal source. Whatever the choice of working fluid, it is used to drive an axially-spinning electricity generator, as with wind and water turbines.

Due to the spinning generator, these generation mechanisms provide AC power. Diesel generators, the most common type of off-grid internal combustion generator, run more efficiently at higher loads, dependent upon their given capability. Compared to wind and water based generators, combustion engines have a far more constant output, meaning that less money or energy needs to be spent to stabilise their AC current output.

1.2.4. Summary of electricity supply technologies

Of the energy supply technologies that are commonly used for off-grid systems, and which are likely to be used in the future, only photovoltaic panels produce native DC output. Because of the decline in per-unit cost of PV panels, seen in Figure 8, they are often cited as the electricity supply technology of choice for off-grid applications, particularly where there are no options for micro-hydro generation.

Axially-spinning generators that generate DC output are called dynamos. The use of dynamos is rare in modern applications, because mechanical wear of the commutator and brushes in the dynamos reduces the lifetime of such devices. The use of dynamos is generally limited to low power applications, where a small amount of DC power is needed and an AC generator with an AC-to-DC converter would be inefficient (see section 1.1.1 for a discussion on AC-to-DC conversion). Axially-spinning AC generators, or alternators, with modern power conversion electronics tend to be more efficient and cost effective than dynamos for all but the lowest-power applications.

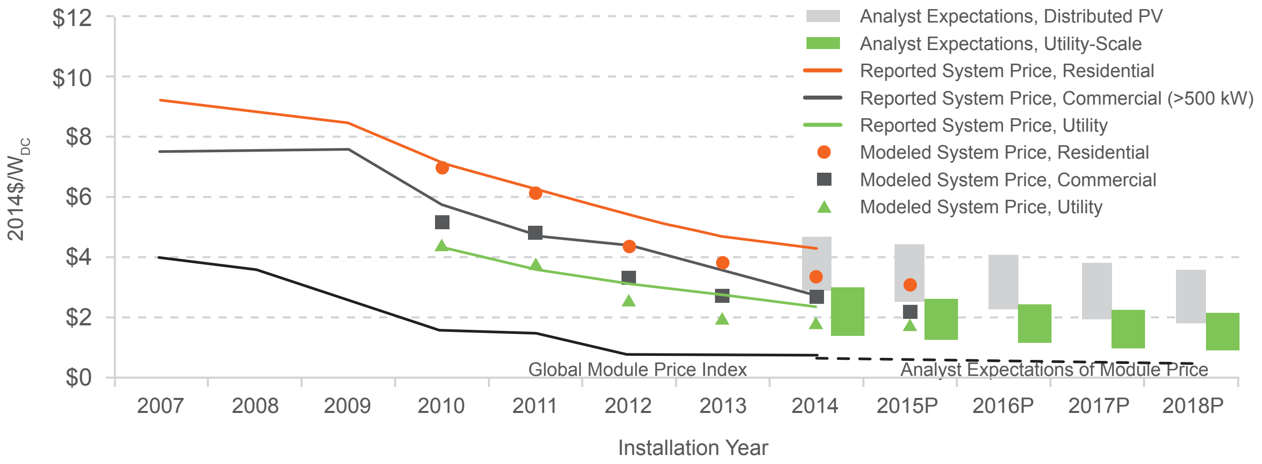


Figure 8: Trends in solar PV panel prices, in US$ per watt, for the United States (Feldman et al. 2015). The red line indicates the price of electricity from photovoltaic panels without any other associated systems costs, such as installation fees.

1.3 Electricity distribution technologies and terminology

The nomenclature for the size of electricity transmission and distribution systems is not standardised. Locations that are “off-grid” are defined as not being connected to a central electricity distribution grid, whereas “on-grid” locations will have such a connection (even if that connection does not reliably supply electricity at all times of the day). Off-grid electricity distribution systems can be defined by (1) their total electricity generation or carrying capacity, expressed here in kilowatts (kW); or (2) the number and types of loads that they supply, ranging from a single appliance with integrated electricity generation to multiple loads within a single building, to multiple buildings in a community, to multiple communities. The grid size definitions that are used in this report, listed below, are informed by Alstone et al. (2015) and Holmes et al. (2015) and are primarily based on the electricity generation capacity of the system, as seen in Figure 9.

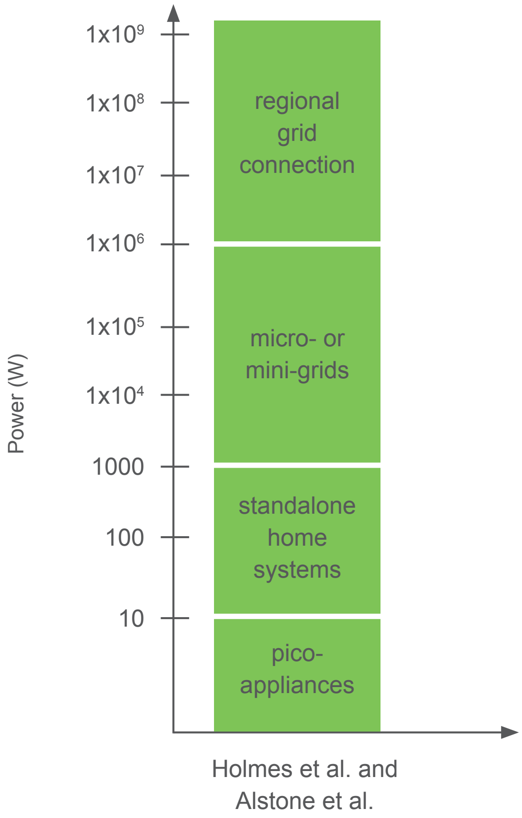


Figure 9: Grid size definitions from Holmes et al. (2015) and Alstone et al. (Alstone et al. 2015a).

However, it should be noted that grid size definitions from different sources vary. The grid sizes in Figure 9 and other terms used in the off-grid community are approximately defined as follows:

Pico-solar systems, or **pico-appliances** are defined as appliances that are directly connected to an electricity generation source, nearly always a solar panel, and consume less than 10 W of electricity. The pico-solar lantern that provides light and power for mobile phone charging is the canonical example. When an appliance is connected to solar power, it is sometimes referred to as a solar pico system (SPS).

Solar home systems are defined loosely, in terms of generating capacity, as systems that provide 10-2000 W of power, for a single home or business unit, from a combination of photovoltaic panels and batteries. The smaller systems in the developing world are generally completely DC (in generation and usage), under 200 W capacity, and have met considerable deployment success due to recent finance and marketing schemes enabling poor customers to use mobile pay-as-you-go (PAYG) payments to circumvent the problem of high upfront system costs.

Stand-alone PV systems for productive uses of energy are similar to solar home systems. These are PV and battery systems, but connected solely to a device for a particular productive use, such as a refrigerator, water pump, or mill.

Nano-grids, in the off-grid community, are generally referred to as grids that link up multiple households, but perhaps not the entire village or communityperhaps around 20-30 households. Alternatively, in a developed world context, following a survey of current vendor offerings, Navigant defines nano-grids as delivering up to 5 kW of power for off-grid systems (Asmus and Lawrence 2014). Navigant also asserts that, because nano-grids are restricted to building scale, they are technically simpler and face fewer regulatory obstacles than do micro-grids.

Micro/mini-grids are defined as having a generation capacity between 1 kW and 1,000 kW. Thus, they can typically supply an area from a single school or hospital to an entire rural community.[12]

---

[12] In the 'On-grid' world, the U.S. Department of Energy defines a micro-grid as "...a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro-grid may connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode." (https://building-microgrid.lbl.gov/microgrid-definitions).

Regional grids have a generation capacity above 1,000 kW.[13]

This report uses the nomenclature adopted by the off-grid electrification community, and the content of this report primarily applies to micro/mini-grids.

1.4 Electricity using technologies

A micro-grid electrical system can enable the use of energy to deliver services in homes and small businesses. Productive uses of energy, defined as uses that can generate income, are enabled by appliances, just as increased healthcare, entertainment, and education can be enabled by appliances. Table 1 documents typical end-use services that may be provided by electrical appliances.

Service	Electrical appliances
Sustenance	Appliances are used to heat food and water for cooking and to cool food and water for preservation. Mechanical appliances can be used to process food.
Temperature control	Air conditioners and fans reduce the perceived temperature, while heating elements or heat pumps increase it.
Transport	Particularly in rural, off-grid communities, where electrified mass transport is virtually unknown, the use of electricity for the transport of goods[14] or people is rare. However, the availability of electric bicycles, scooters, motorcycles, cars, and even transport trucks has been steadily increasing in the last five years, while their prices have been falling.
Information processing and exchange	Mobile phones, televisions, personal computing devices such as laptops, tablets, and smart phones that are used for information processing and exchange are composed of integrated circuits, radios, displays, and speakers
Manufacturing	Production and manufacturing include activities such as mechanical and thermal manipulation of materials.
Lighting	Light emitting diodes and other electric lighting technologies

Table 1: End-use services that can be provided by electrical appliances.

The appliances that provide these services are in turn made of fundamental electrical components, as documented in section 1.4.1. While the variety of available AC and DC appliances is large, these appliances are constructed from a finite number of electrical component types. The next sections examine the technology trends for the most common fundamental components that constitute DC appliances. As a result, some sense of the future of the market for DC appliances can be gained.

1.4.1. Fundamental components of electrical appliances

Table 2 shows an overview of common household electrical components and their native power supplies.

---

[13] In the developed world, the terms milli-grids or mini-grids are occasionally used to refer to small portions of a utility grid, or small utility grids (Smart Grid Interoperatibility Panel 2016).

[14] Other than liquids via pipeline.

Category	Component	Native power supply	Explanation
Motors	Electric motors	AC or DC	Motors are either designed to take an AC or DC power supply. Universal motors exist that can be run on either AC or DC power, but their components wear quickly.
Lighting	LEDs	DC	Though AC LEDs exist[15], DC LEDs dominate the current lighting market.
	Fluorescent lamp	AC or DC	Fluorescent lamps can be run natively on a DC power supply, though there are severe control and lifetime issues unless the plug voltage is greater than 250 V.
	Incandescent lamp	AC or DC	Incandescent laps can run on either AC or DC power.
Devices using electronics	Integrated circuits	DC	Integrated circuits typically run on 20 V or less of DC power.
	Radios	DC	While radios broadcast an AC signal, since modern radios are digital radios, their native power input is DC.
	Mobile phones	DC	Most mobile phone chargers convert 220 V AC power to a 5 V DC supply for charging a phone battery
	TVs/displays	DC	Modern LCD displays are constructed from integrated circuits, so they take DC power. Older cathode ray technology uses a combination of AC and DC power.
Heating	Electric heating elements	AC or DC	While some resistive electric heating elements can be used with either AC or DC power, they are typically designed for one or the other.
Cooling	Fans	AC or DC	There are many examples of both AC and DC-powered fans. Historically AC fans have been more readily available, but DC fans are becoming relatively more common compared to their past availability.
	Air conditioners	AC or DC	Typically, cheaper air conditioning systems use an AC input to power the gas compressor required for air conditioners, but more advanced systems use an inverter to switch to DC to have a variable speed motor for increased temperature control.
Energy storage	Battery energy storage	DC	Batteries of all chemistries are charged and discharge with DC power.
	Kinetic energy storage	AC or DC	Flywheels store energy as kinetic energy, so they are charged using electric motors, and discharged using electric generators. Either of these components can be an AC or DC compatible component.

Table 2: Summary of fundamental components and their native power supplies.

---

[15] *http://www.ledsmagazine.com/articles/2006/05/running-leds-from-an-ac-supply.html*

1.4.2. Electric motor technologies

Electric motors can either be designed to accept an AC or DC power supply. AC motors may be either universal, synchronous, or asynchronous (induction) motors. DC-powered electric motors can be divided into either (1) brushed DC motors or (2) brushless DC motors, as seen in Figure 10.

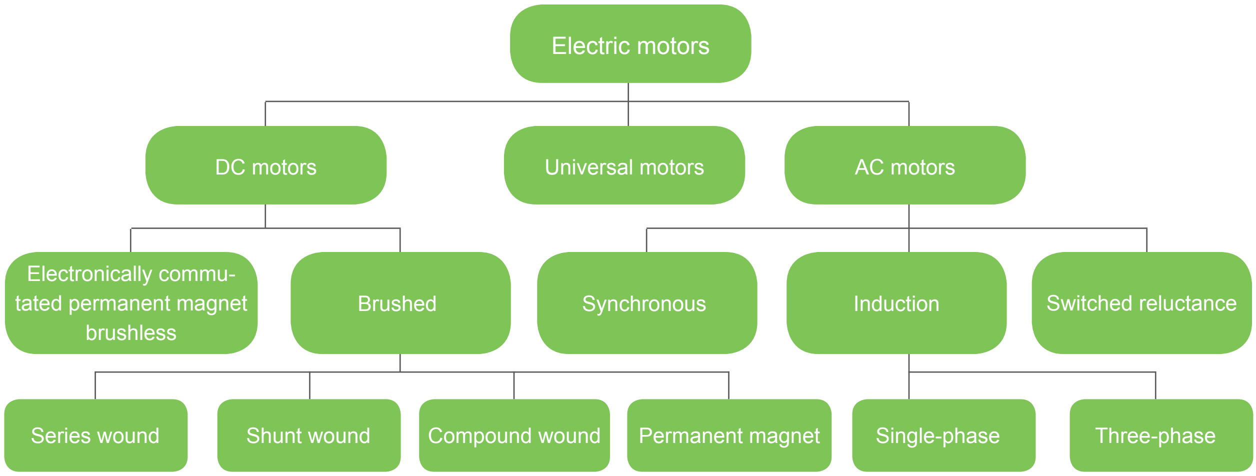


Figure 10: Classifications of electric motors adapted with modifications from Waide and Brunner 2011 and originally attributed to De Almeida A.T., et al. (2008a).[14]

In general, the efficiency of electric motors scales with size, ranging from approximately 50% efficiency for motor sizes of 0.1 kW to over 95% efficiency for motor sizes of 1 MW or larger (IEA 2015). The change in efficiency with motor scale is partly dependent on economic effects, where there is more incentive to design larger motors that consume more electricity in a more efficient manner. For electric motors, the majority of energy efficiency gains in electric motors between 2015 and 2025 are likely to come from price reductions and greater uptake of existing high efficiency motors, rather than the development of new technology.[16]

While brushed DC motors are inexpensive, the brushes mechanically wear over time, mandating replacement after perhaps 2-5 years of service for home-appliance sized motors. The universal motor, a type of brushed DC motor, can be powered by both AC and DC power sources. Universal motors are powerful for their weight, but in addition to mechanical wear issues from the brushes, they are noisy and inefficient, though these problems are somewhat less severe when the motor is operating with DC electricity.

Brushless DC motors include a number of different subtypes, and they can generally match or exceed the energy efficiency of similar-sized AC motors, though this is application dependent. The energy efficiency of these motors can reach 80-90%, and they can be run on either an AC or DC power supply. Brushless DC motors are today costlier and more complex than AC motors of similar size and efficiency because of additional electronic components that are required for their operation. The key areas of improvement to make brushless DC motors more appropriate for off-grid systems are documented in Table 3.

---

16 nb: Universal motors may run on either AC or DC electricity, and that electronically commutated permanent magnet brushless motors are actually AC motors that take a DC input and invert it.

Category	Improvements
Cost	Reducing the number of motor winding phases from 3 to 2 for simple applications such as cooling fans Reducing the cost of electronics and the number of electronic components
Simplification of manufacturing	Embed the electronics within the motor Make the motor easy to install and use through “plug and play” technology

Table 3: Improvements necessary for increased uptake of brushless DC motors in off-grid applications (Price 2016).

Brushless DC motors rely on an associated inverter to generate an alternating current waveform in the stator, rather than using a commutator as in brushed DC motors. Thus, brushless DC motors are essentially AC motors, with the DC-AC conversion occurring internally within the motor. Because of this feature, brushless DC motors can be run at variable speeds by electronically modifying this waveform, unlike an AC motor whose speed is fixed by the AC line frequency. Therefore, an area of large potential energy efficiency savings in electric motor appliances is through the use of variable speed drives (VSD) with brushless DC motors to precisely match the speed of the motor to the speed needed for the application (Fleiter et al. 2011).

Waide and Brunner (2011) cite the value of VSDs as being due to the fact that:

> Many motor applications have high operating hours but variable loads. Even with the relatively flat efficiency curve of larger IE3 motors (between 50% and 125% load), there are still large gains to be made by adapting motor speed and torque to the required load. The largest benefit comes with pumps and fans in closed loops for which power consumption varies as a cubic power of their rotational speed. In traditional equipment, the load adjustment is made by introducing artificial brakes (control valves, dampers, throttles, bypasses, etc.). In air-conditioning systems, the temperature and flow control of pumps and fans can be achieved with VSDs, reducing on/off cycles and providing a more stable indoor climate. In constant torque loads such as air compressors and horizontal conveyors, an adjustable speed control also has efficiency benefits by running the system with modulation more stably than with on/off cycles. Traditional speed and torque control uses either two-speed or multi-speed motors, with several motors working in parallel or with changing gears (step or continuous). Electrical switching (star/triangle) or other methods are also used. Early on, DC motors were used to alter speed continuously, but they are used less nowadays because of increased wear (brushes).

However, AC induction motors and synchronous motors, when connected to an AC-AC converter, can also be used in VSDs, so VSDs are not limited to DC architectures. The market penetration of VSDs is expected to increase dramatically as the electronic control elements necessary for their operation become less expensive.

1.4.3. Lighting technologies

The growth rate of adoption of light emitting diode (LED) technology for lighting is evidence that they are the lighting choice for the future, particularly in situations where the electricity supply is expensive or constrained, thus making energy efficiency of paramount importance. As seen in Table 4 and Figure 11, LED technology is expected to advance considerably between 2015 and 2025, leading to increased energy efficiency and decreased price for products.

Metric	2015	2025	Source
Specific energy use [lumens/watt]	80	175	US Department of Energy 2014
Average capital cost per unit [$]	7	3	

Table 4: Key metrics for LED lighting components in 2015 and 2025

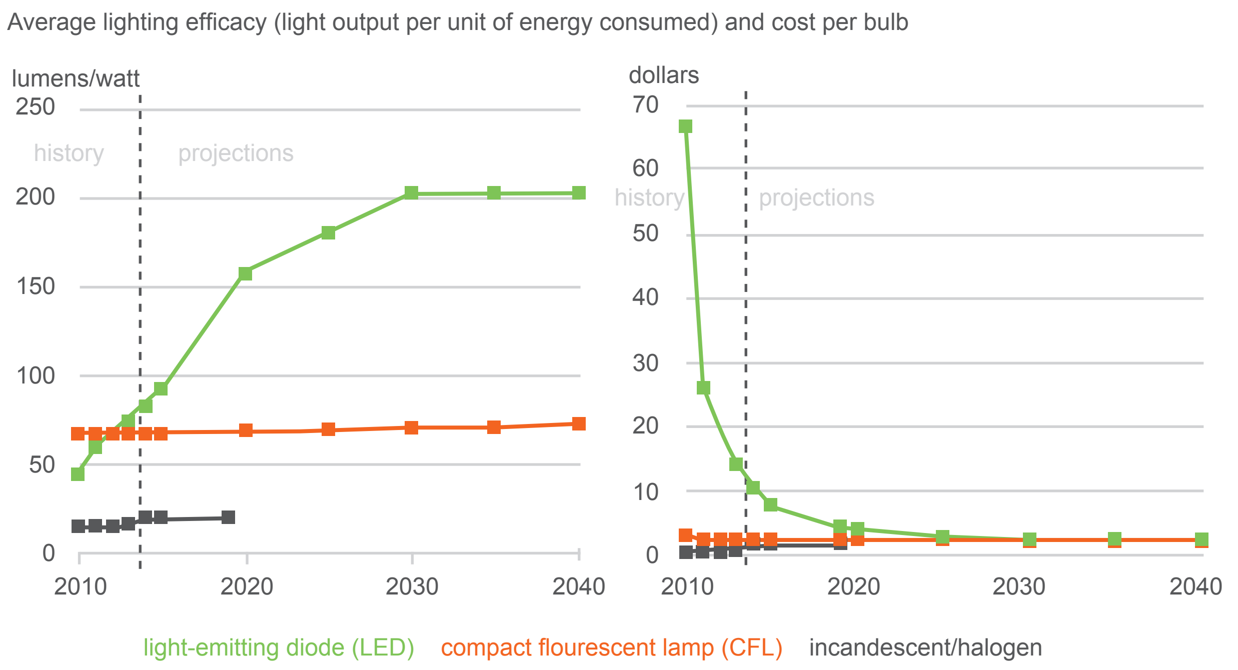


Figure 11: History and projections for energy efficiency and cost of LED, CFL, and incandescent lighting technologies (US Department of Energy, Energy Information Admistration, 2014).

LEDs designed for use with AC power will have an internal rectifier to convert the AC electricity into a DC waveform. Thus, different LED specifications are needed for AC and DC power supplies. While some experimental native-AC LEDs exist[17], current commercially available LEDs designed for use with an AC electricity supply will have 8-16% lower efficiency than LEDs designed for use with a DC electricity supply, because of the AC-DC inverter required to be integrated into each light fixture (Thomas et al. 2012).

1.4.4. Devices using electronics

Electronics devices include personal computers, tablets, smart phones, televisions, and other devices to manipulate and transmit information. The fundamental electronic components that make up these devices include integrated circuits, radios, and displays. Electronic components run on native DC power, so electronics connected to

---

[17] *http://www.ledsmagazine.com/articles/2006/05/running-leds-from-an-ac-supply.html*

an AC grid require an AC-DC conversion step between the grid and the DC. The share of household electricity use that is devoted to electronics has been increasing, with the IEA estimating that the average global share is 15% and rising.[18]

Electronic displays are essential for the transmission and manipulation of information. While modern displays are often made using LED lighting components, they are considered a fundamental electrical appliance component here because of their ubiquity in many appliances in the home environment, including TVs, laptops, phones, and increasingly "smart" appliances. Because they consist of lighting and electronic components, modern displays which incorporate LED lighting are natively DC-powered. The energy efficiency of displays has been increasing because of a number of technology improvements, including the implementation of LED-LCD, OLED, and other modern display technologies and the inclusion of modern power electronics to reduce standby energy consumption (Park 2011).

1.4.5. Cooling and heating

During operation, any electrical component will produce heat energy as a function of its internal electrical resistance. Normally, this energy is considered to be wasted, or even dangerous, when emitted by an integrated circuit or an electric motor. In contrast, electric heating elements are designed to convert electricity to heat during operation. Electric heating elements are large resistors that convert electricity into heat. They can be designed to operate on AC electricity, DC electricity, or both. The efficiency of electric heating elements is technically 100% since all the electricity is converted to heat.

However, electricity is considered the highest quality form of energy, while heat is considered the lowest quality form.[19] Thus, it is actually more efficient to use electricity to drive a motor in a compressor in a heat pump appliance. Such appliances (air conditioners are one common implementation of heat pump technology) can have efficiencies of approximately 350%.[20] DC-native heat pumps require both electronics and DC motors to drive the compressor. Fans are the most commonly implemented form of cooling in off-grid contexts. Cheap DC-powered fans using brushed DC motors are widely available. DC fans with brushless DC motors, whilst they last much longer, are still more expensive in off-grid contexts and hence less common. AC fans have much less speed control, but are cheap and are also widely available.

1.4.6. Energy storage

Feasible energy storage technologies include those that use thermal energy, chemical energy, electrical energy, gravitational energy, or kinetic energy, as shown in Table 5.

Of the energy storage options in Table 5, only chemical energy storage has achieved significant penetration in the off-grid market (kinetic energy storage has been used in many data centres). Batteries and fuel cells which store chemical energy are both the most ubiquitous and fastest-growing method of storing excess electrical energy, with Citibank estimating that the global energy storage market will reach 240 GW by 2030 (Savvantidou et al. 2014) from less than 10 GW in 2015 (Kempener and Borden 2015), with consequent decreases in unit cost because of economic returns to scale.

Batteries and fuel cells are charged using DC electricity, and when discharged they generate DC electricity. Flywheel energy storage systems, because of the rotary motion of the flywheel,

---

[18] *http://www.renewableenergyfocus.com/view/3199/dc-microgrids-a-new-source-of-local-power-generation/*

[19] *In engineering terms, electricity has a high exergy and the exergy of heat will depend on the temperature, with lower temperature heat having lower exergy values.*

[20] *This definition of efficiency is called the coefficient of performance (COP).*

Class	Example application to the micro scale
Thermal energy storage	Solar energy is used to heat water, which can be used for cooking, and bathing applications.
Chemical energy storage	Batteries or fuel cells can be used to store excess electricity produced by PV panels during the day time for use at night.
Electrical energy storage	Capacitors can be used to store electrical charges inside electrical appliances for short periods of time.
Gravitational energy storage	Water is pumped up a hill using excess electrical energy, and can be harvested by letting that water flow down the hill again, through a turbine that converts the energy from the flow of water into mechanical or electrical energy.
Kinetic energy storage	Flywheels store kinetic energy through their spinning disks. Flywheel systems can last a long time (decades) and store a large amount of energy, but are expensive compared to battery technology, for instance, due to needing a vacuum to reduce spinning resistance.

Table 5: Classes of energy storage

generate AC electricity (Active Power) but at a variable frequency and voltage, which must then be converted to DC for either native DC or regulated AC use (Elserougi et al. 2012). The cost per unit of energy stored for battery, fuel cell, and flywheel systems has been steadily decreasing. For example, the historical and projected learning rate for lithium-ion batteries is 15%.[21]

1.5 Summary of fundamental electrical technologies

The energy supply, conversion, storage, and appliance technologies exist to construct viable DC micro-grid connected to DC supplies and loads. Furthermore, the next ten years will see significant increases in the energy efficiency of these components. However, the implementation of DC micro-grids with DC electricity supplies and native DC loads will depend on factors including cost and regulatory barriers, explored in the next section.

---

[21] *The learning rate is the decrease in unit cost per doubling of installed capacity.*

MICRO-GRID SCALE DC AND AC SYSTEMS

Off-grid villages and homes may gain electricity access with a micro-grid. It is evident that micro-grids connected to distributed energy generation are already proliferating in areas that are not served by the grid, and that this growth will accelerate. The benefits of constructing AC versus DC grids depends on system parameters that will be explored in this section.

2.1. Mixing AC and DC

The widespread adoption of 120V or 230V AC distribution networks has led to a wide availability of AC appliances. In general, appliances configured to accept AC power cannot accept DC power, though lighting fixtures are generally an exception to this rule. Even in appliances where some or all the components run on DC power, the appliance will have its own internal electricity conversion hardware to convert the input AC waveform into the appropriate DC voltage, which is often accompanied by a significant energy conversion loss. For this reason, there are potential issues when mixing AC appliances with a DC power supply, and vice-versa.

Appliances are typically designed to operate solely on DC or AC power. A review of DC appliances by Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH[22] (GIZ 2016) reveals that, currently, the only appliances with the capability to run on either AC or DC power are those which incorporate universal electric motors. Table 6 provides an overview of how various classes of appliance are able to operate with a mixed AC and DC power supply.

Electrical component	Feasibility of mixing power supply
Electric motors	Commutated series-wound motors, otherwise known as "universal motors", can operate on either AC or DC power supplies. Other classes of electric motor are designed to operate solely on either AC or DC power.
Lighting: LEDs and compact fluorescent bulbs	LEDs which have been designed for use with grid-connected AC are built with internal rectifiers and transformers to transform an input AC waveform into a DC waveform at an acceptable voltage. Such bulbs can be used with a DC power supply as well however, even though they are not designed for it, as the DC electricity will pass through the internal rectifier with no significant effects.
Devices using electronics	Microelectronics must run on DC electricity.
Heating: resistive heating elements	May run on either AC or DC electricity
Cooling: fans and air conditioners	Fans utilise electric motors, so their capacity for running off both AC and DC electricity depends on the type of electric motor used. Air conditioners also use electric motors for the pumps and compressors, so the same restrictions apply.
Battery storage	Charging and discharging only possible with DC electricity

Table 6: Mixing AC and DC power supply with appliances, matching the categories in Table 2.

---

[22] *Approximately translated as German Corporation for International Development.*

The obvious alternative to constructing a household with appliances able to operate on both AC and DC power, is to perform conversions at the household level. Figure 12 is a schematic for a household with an AC wiring system which integrates AC and DC power supplies with AC and DC appliances.

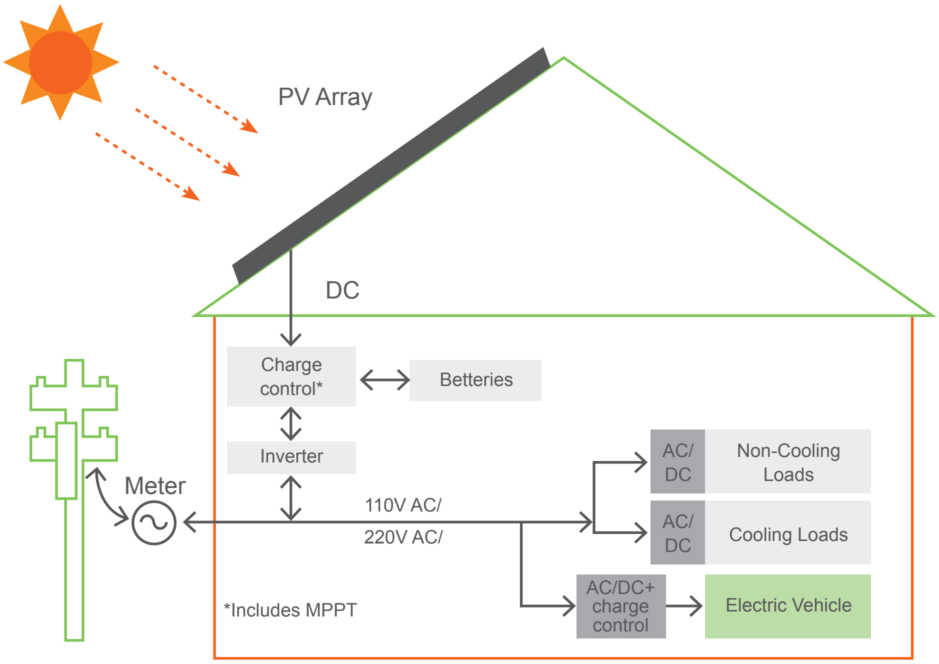


Figure 12: A schematic of a household AC system with DC power input from a PV array Garbesi et al. 2011.

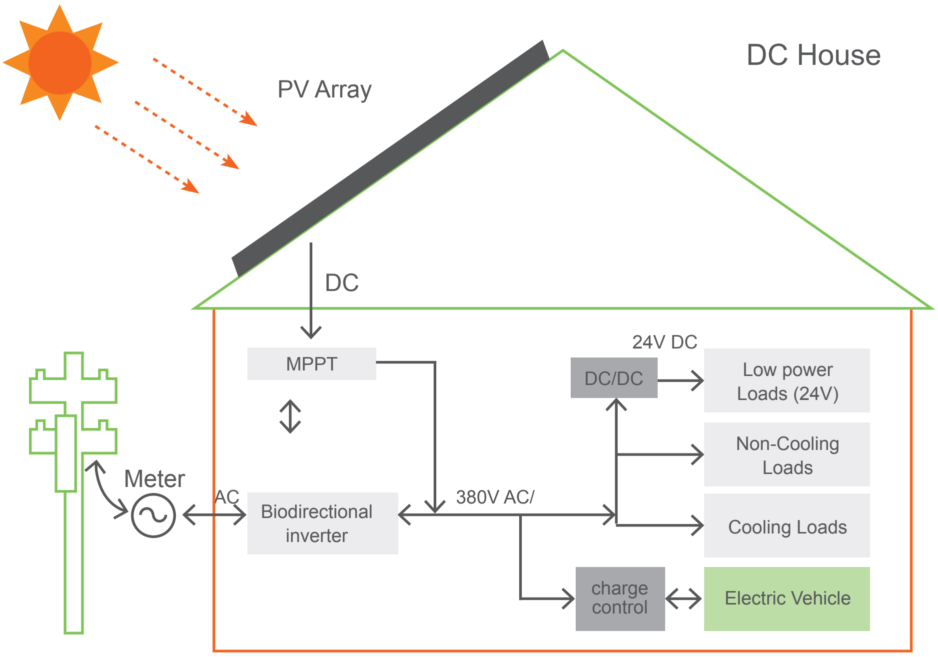


Figure 13: A schematic of a household DC power system, with potential AC power input from the grid which is converted to DC Garbesi et al. 2011.

Figure 13 is a schematic for a medium voltage DC household wiring installation which integrates AC and DC power supplies with DC-only appliances.

The Lawrence Berkeley National Laboratory (USA) study, which produced both of the configurations seen in Figure 12 and Figure 13, concluded that households with mixed AC and DC appliances are feasible, given appropriate investments in power conversion infrastructure. In particular, the integration of multiple AC power sources, for example grid power sources with micro-hydro generation, requires frequency regulation and phase-matching electronics, which add to overall system cost. The trade-offs between efficiency and capital costs for different configurations are explored in section 2.5.

Backhaus et al. (2015) examine the feasibility of mixing rotational (AC) electricity generation sources with DC generation sources and note that these components will have very different response speeds to grid instability, which will complicate the design of control and protection systems in mixed micro-grids. While AC-DC-AC power electronics exist which can integrate AC and DC generation sources, Backhaus et al. (2015) conclude that DC distribution architectures may be more cost effective and energy efficient in this case, as discussed further in section 2.5.

The EMerge Alliance specification for commercial buildings specifies parallel DC and AC electricity distribution architectures (EMerge Alliance; Thomas et al. 2012). In this specification, DC electricity would generally be used for lighting and electronic loads, while the AC distribution system would be used to power legacy appliances. This proposed architecture is adaptable for buildings with existing AC electricity distribution.

2.2 Availability and characteristics of DC appliances

Historically, DC appliances were restricted to the transportation market (automobiles, buses, planes, and trains) because those vehicles supplied native DC power from batteries. The Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH[23] have produced a comprehensive catalogue of native DC appliances (GIZ 2016). The contents of the catalogue provide clear evidence that the availability of DC appliances is increasing, from agricultural equipment such as irrigation pumps and rice polishers, to home appliances such as electric clothes irons and washing machines. The EMerge Alliance also maintains a list of registered suppliers of DC appliances and equipment.[24]

However, many of the products in the catalogue have been integrated with their own PV array and battery system. The availability and uptake of these stand-alone appliances, whether native AC or DC, is a trend which will help to dictate the uptake of DC micro-grids. Increased use of these stand-alone appliances may lessen the need for micro-grids.

Using the GIZ catalogue as a reference, many of the currently available appliances (in 2016) which contain DC motors use brushed DC motors. In general, brushed DC motors are less efficient and feature higher mechanical wear (due to the brushes) than brushless DC motors, though brushed motors are generally less complex and expensive. Brushed motors may require replacement brushes every two to five years, and for off-grid applications, this may pose a challenge where the supplies and expertise to replace these components may be scarce.

2.3 AC vs. DC distribution

Discussion on distribution losses due to electrical resistance must be made with full information. DC distribution systems can be classified by their total system voltage, which is either the stated voltage

---

[23] Approximately translated as German Corporation for International Development.

[24] http://www.emergealliance.org/Products/RegisteredProducts.aspx

(e.g., 12 V) or twice the stated voltage if the system is defined with a negative voltage ground (e.g., a ±12 V system has a total system voltage of 24 V). In contrast, because the voltage in AC electrical systems varies over time, the system voltage is defined as the root-mean-square (RMS) voltage, which is defined as for sine-wave AC systems.

Until very recently, the DC appliance market focussed on mobile applications for cars, trucks, ships, and planes. Since these vehicles typically have a 12 V or 24 V electrical system to correspond to their battery voltage, DC appliances for this market are typically designed to operate on this voltage. The IEEE Smart Villages initiative (IEEE) has focused on 12 V or 24 V systems that mimic these legacy mobile applications (IEEE). This voltage level, while potentially appropriate for powering small appliances, is not suitable for distribution on a micro-grid scale because of the resistive losses that would be incurred.

Large electrical resistance losses can be incurred in a low-voltage DC system when electricity must be transported some distance. Figure 14 shows two series: the normalised resistivity loss for a given wire length and thickness, and the normalised wire thickness that would be need to achieve the same loss. For example, the losses incurred for a wire of a given width and length would be 367 times greater for a 12 V DC system than for a standard 230 V AC system. Alternatively, the wire thickness would need to be 19 times greater to achieve the same losses in the 12 V DC system.[25] Thicker cable insulation is generally needed for AC systems with the same RMS voltage as a DC system, since the insulation needs to be sized for the peak AC voltage rather than the RMS AC voltage.

In general, increasing system voltage will result in lower losses in both AC and DC systems. As will be discussed in section 2.4, 60 V is typically considered the safe voltage maximum for DC systems inside the household. Therefore, the solution has been to use medium voltage DC (normally 380 V DC) or AC (normally 230 V AC) for micro-grid (village-sized) electricity distribution. These medium voltages can then be stepped-down to lower voltages for use in appliances. Boeke and Wendt (Boeke and Wendt) note that, because of the higher system voltage, the non-varying property of DC distribution, and the reduction of skin current effects, 380 V DC distribution needs 63% less cable cross section for the same power loss as 230 V AC distribution.

Some studies, and the EMerge Alliance standard, specify 24 V DC systems for appliances because this standard combines safe power distribution with minimal resistivity losses if the distribution is confined to a single building. Furthermore, many digital devices are built to accept 24 V DC.

The application of DC distribution systems and appliances to applications other than transport is in its infancy. Standards on the voltages and safety components for DC systems are still evolving. Table 7 documents some of the DC electricity distribution standards that are in use in 2016.[26]

---

[25] A complete comparison of AC vs. DC wire thicknesses would need to account for the "skin effect", where AC current flow is concentrated near the surface of the wire.

[26] https://www.itu.int/rec/T-REC-L.1200-201205-I/en

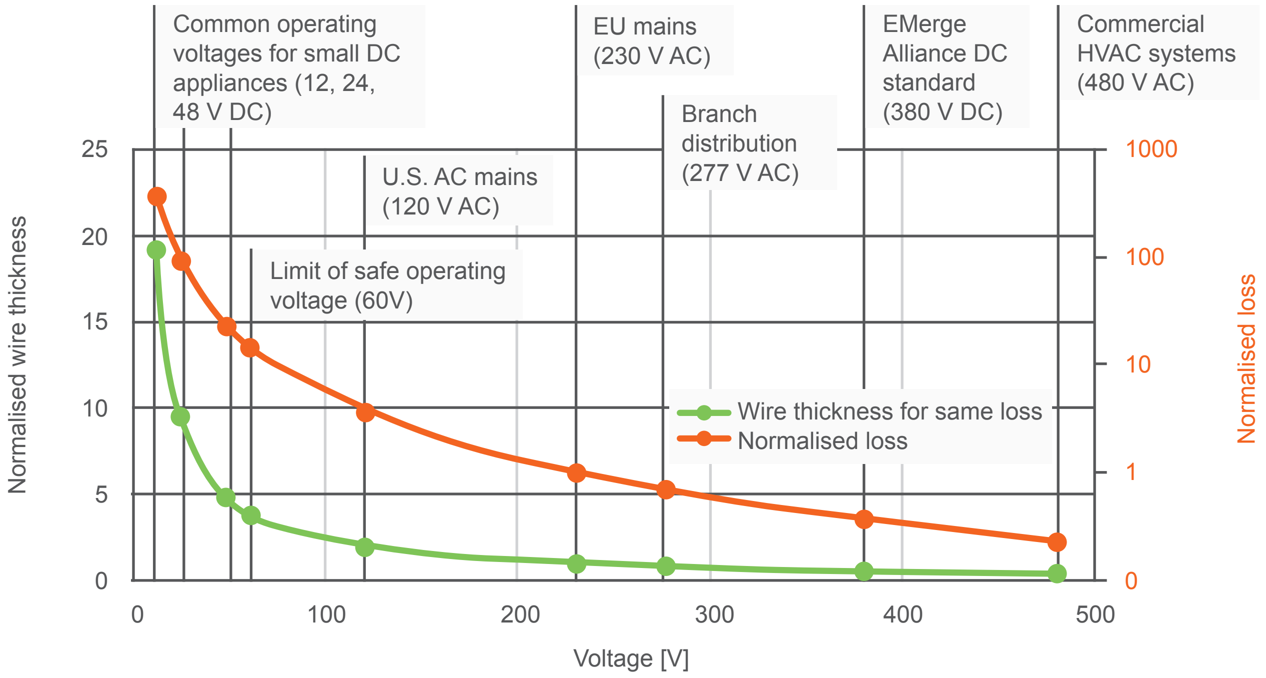


Figure 14: Normalised losses for a given length of wire vs. voltage (orange) and wire thickness needed for the same loss over a given length of wire (blue). Both the losses and the wire thickness are normalised to the European mains voltage of 230 V AC.

Name	Type	Voltage	Notes
EMerge Alliance[26]	DC	380 V / 24 V	Developed for use in commercial buildings, and has been trialled for use in data centres. This standard was developed in U.S. but has been expanding to regions of the world without grid access, for example South East Asia.[27]
Institute of Engineering and Technology Code of Practice for Low and Extra Low Voltage Direct Current Power Distribution in Buildings	DC	24 V	This code of practice aims “to ensure the safe, effective and competent application of cabling / wiring installations for low voltage d.c. power distribution in buildings.”[28]
IEEE Sunblazer	DC	12 V / 24 V	The IEEE Sunblazer kits are sized for either 12 V or 24 V electricity generation and distribution, depending on the model purchased.
DCG + C	DC	380 V	European building focussed distribution standards project.[29]

---

[27] *http://www.emergealliance.org/*

[28] *http://www.renewableenergyfocus.com/view/39533/emerge-alliance-expands-dc-power-initiative-to-south-asia/*

[29] *http://www.theiet.org/resources/standards/lvdc-cop.cfm*

[30] *http://www.dcc-g.eu/*

Name	Type	Voltage	Notes
International Telecommunications Union standard L.1200	DC	400 V	Set of standards for power input to professional ICT and telecommunications equipment.[30]
European Telecommunications Standards Institute	DC	400 V	Set of standards for power input to professional ICT and telecommunications equipment (European Telecommunication Standards Institute 2011).

Table 7: DC distribution standards

Because all their electronics are native DC loads, data centres have been arguably the first widespread application for DC micro-grids. In their review of DC data centre conversions, Johnson and Hebert (2012) found that efficiency gains were between 15-40%. However, data centres powered by DC electricity are a very distinct case of application of DC micro-grids. Studies which examine DC micro-grids with a greater variety of loads are much less common, and further work is needed, as explained in section 2.5.

2.4 AC vs. DC safety

Both AC and DC electricity architectures can be hazardous, but there is much misinformation in the debate around the safety of AC vs. DC systems. There are two primary safety concerns for electricity: (1) electric shock, were electrical current passes through part of a human body; and (2) arc flash, which is an electrical discharge through the air that can cause burns.

For electrical shocks in humans, the amount of current flowing through a body part is the most important factor. In general, it takes less AC current than DC current to do the same damage because AC current causes muscles to contract and thus may inhibit an individual from letting go of the object causing the electric shock. This is further explained in Table 8 and Figure 15.

Electrical arc flash has been cited as being a safety concern for DC power systems, and there is currently no standard for calculating the arc flash hazard from DC power systems.[31] In general, DC electricity supply systems need larger equipment in order to prevent arcing than AC systems. This is in large part due to the fact that because the AC voltage alternates between positive and negative voltages, when the voltage crosses zero on an arcing AC system, the arc will be extinguished. In contrast, the voltage in a DC system does not cross zero, so more complicated equipment is needed to extinguish the arc. Thomas et al. (2012) note that:

> AC circuit breakers function by opening the circuit, which typically forms an arc that is extinguished when the voltage waveform passes through zero. Arcs in high voltage (450 V) DC wiring systems can occur through a loose wiring connection or damaged insulation between cables of different polarity or between an electrical circuit and ground…DC wiring can cause arcing even at currents under the threshold at which the circuit protection operates. Thus, some DC wiring may need additional arc-quenching insulation and fault- detection and special signage for first-responders and other emergency service personnel.

However, new technologies, including magnetic arc breakers and switched interlocks can alleviate this safety hazard at a reasonable system cost (Asmus and Elberg 2015). AC arc flash guidelines are

---

[31] *http://www.ecmag.com/section/safety/know-your-arc-dc-arc-flash-calculations*

covered in publication IEEE 1854. However, the current state of DC circuit protection and galvanic isolation technology means that such equipment is both more expensive and physically larger than counterpart AC technology. Electronic circuit breakers, which use microelectronics to detect an arc and break the DC circuit, would be smaller and less expensive than existing technology. However, they are not yet commercially deployed because further development of the technology is needed, and new regulations would have to be devised to certify their design, construction, and installation.

In general, the cited voltage safety limit for human contact with either AC or DC electrical systems ranges from 30 to 60 V. The EMerge Alliance notes that electrical “power over 30 Volts is not safe when conductors are exposed without insulation”. The safety differences between AC and DC electrical systems arise from (1) their different waveforms; and (2) different RMS voltages. An AC electricity supply cycles between positive and negative voltages, as seen in Figure 1. Thus, it has a “zero-crossing point” where the voltage is zero twice each cycle. For a 50 Hz system, the standard in Europe, the voltage is zero 100 times per second. DC systems, on the other hand, supply electricity at a constant voltage that is never zero. The “let go” current is defined as the “is the lowest level of current passing through a human subject through an electrode held in the hand that makes the subject unable to open his hand and drop the electrode” (International Electrotechnical Commission 2005). Because of AC’s varying waveform, it can cause muscles to contract when receiving an electrical shock, and thus the ‘let go’ current for AC is lower than that for DC electricity.

A

Zones	Boundaries	Physiological effects
AC-1	Up to 0.5 mA curve a	Perception possible but usually no “startled“ reaction
AC-2	0.5 mA up to curve b	Perception and involuntary muscular contractions likely but usually no harmful electrical physiological effects
AC-3	Curve b and above	Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected
AC-4[1]	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest. breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1-c_2	AC-4.1 Probability of ventricular fibrillation increasing up to about 5%
	c_2-c_3	AC-4.2 Probability of ventricular fibrillation up to about 50%
	Beyond curve c_3	AC-4.3 Probability of ventricular fibrillation above 50%

[1] For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed As regards ventricular fibrillation, this figure relates to the effects of current which flows in the path left hand to feel. For other current paths. the heart current factor has to be considered.

B

Zones	Boundaries	Physiological effects
DC-1	Up to 2 mA curve a	Slight pricking sensation possible when melting, breaking or rapidly altering current flow
DC-2	2 mA up to curve b	Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects

DC-3	Curve b and above	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected
DC-4[1]	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1-c_2	DC-4.1 Probability of ventricular fibrillation increasmg up to about 5%
	c_2-c_3	DC-4.2 Probability of ventricular fibrillation up to about 50%
	Beyond curve c_3	DC-4.3 Probability of ventricular fibrillation above 50%

[1] For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation this figure relates to the effects of current which flows in the path left hand to feel and for upward current. For other current paths the heart current factor has to be considered.

Table 8: Time and current zones for (A) AC 15-100 Hz and (B) DC hand to feet pathway. Adapted from International Electrotechnical Commission 2005.

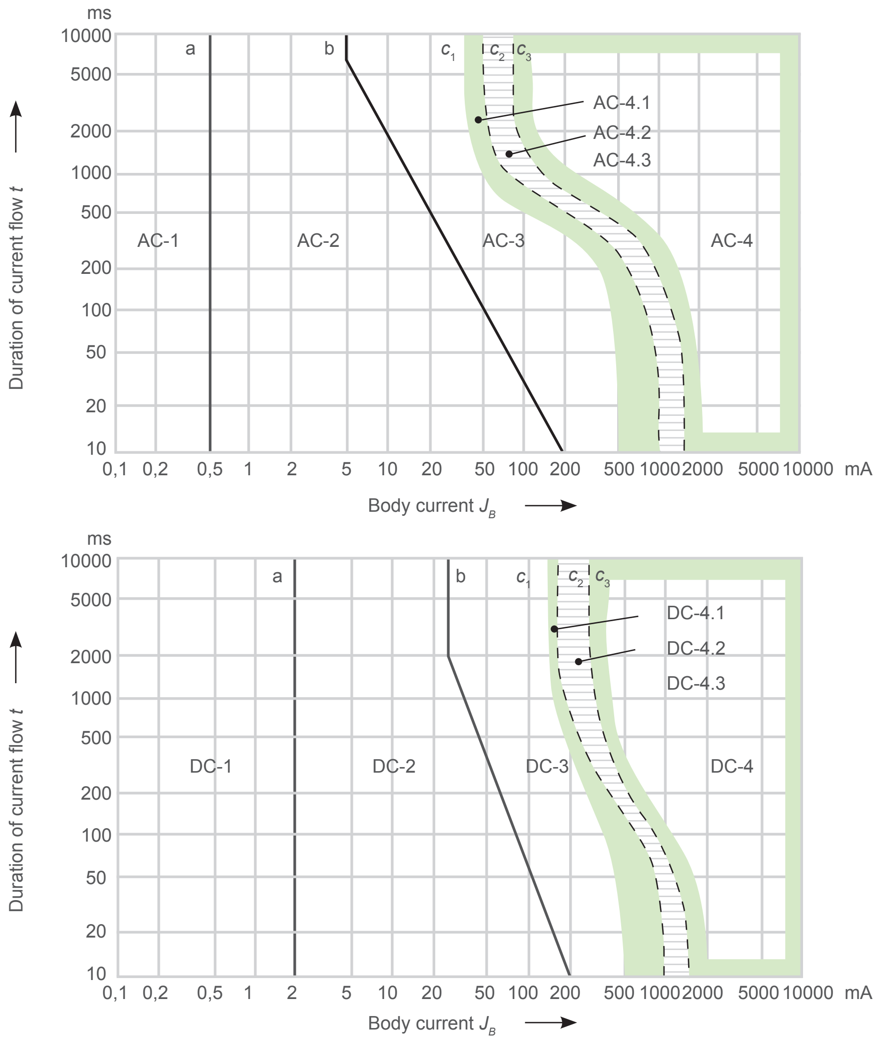


Figure 15: Graphical time/current zones from Table 8 of effects on (A) AC currents 15-100 Hz and (B) DC currents on persons for a longitudinal upward current path. Adapted from International Electrotechnical Commission 2005.

Figure 15 shows these current zones defined in Table 8 graphically. Both Table 8 and Figure 15 are taken from the International Electrochemical Commission's technical specification on the effects of electrical current on human beings and livestock. It is clear from Figure 15 that, for electrical shocks, it takes a higher amount of DC current to cause the same physiological effects as a given amount of AC current.

To date, examples of functional DC micro-grids largely consist of high-technology data centres, which maintain grid connections. These data centres typically use the 380 V DC standard, and Backhaus et al. (2015) note that safety equipment, including circuit breakers, is available for these DC voltages. They assert that assuring safety in DC systems is a concern for the capital cost of equipment, rather than an absolute concern for safety. While the safety of DC micro-grids in data centres and other high-technology buildings has been demonstrated, it is not necessarily the case that the safety of those systems, installed and maintained in highly controlled, regulated, and standardised environments, can be replicated in off-grid communities around the globe.

The existing examples of DC micro-grids, both below 60 V and at 380 V, demonstrate that DC architectures are, when appropriately designed, as safe as AC architectures. However, the safety standards, equipment, and expertise for DC architectures are all less mature than for AC architectures, and the specialised circuit breakers and protection technologies for DC micro-grids are active areas of research (Salomonsson et al. 2009; Salomonsson and Sannino 2007). Therefore, constructing a safe DC grid may cost more than constructing a safe AC grid. Furthermore, at voltages below 60 V, DC systems are currently limited to a power capacity of approximately 1 kW in order to keep the system current within safety limits. Significant investment in technology maturation and regulatory development is needed for DC systems to be deployed at scale.

2.5 AC vs. DC micro-grid efficiency, cost, and robustness

Micro-grids connected to distributed energy generation will likely proliferate in areas that are not served by the grid. The balance of energy efficiency, robustness, and capital cost for AC vs. DC micro-grids will differ depending on specific applications. Universal claims of better efficiency, lower copper cost, or lower capital costs for either AC or DC micro-grid architectures should be questioned because, as will be shown, these metrics are highly dependent on the specific system design for a specific context.

2.5.1. Grid- and appliance-level energy efficiency

Systems of DC distribution grids connected to DC appliances may be more efficient than similarly-sized AC systems for three reasons: (1) if a higher distribution voltage is used for DC systems (say, 380 V DC), this may lead to lower resistive losses; (2) if DC-native electricity generation and DC-native loads are used in the system, then energy losses from DC-AC-DC conversions are eliminated in an all DC systems; and (3) DC-native appliances are in some cases more efficient than their AC counterparts.

Wire losses. The resistive energy losses in electrical wire are related to the system voltage as shown in Figure 14 - raising the voltage and lowering the current decrease these losses. Standard AC mains voltage is between 100–240 V, which allows for relatively efficient transmission across moderate distances. The standard plug voltage for small appliance DC is below 50 V, so large electrical losses occur if this voltage is transmitted outside of a home. However, DC micro-grid transmission distances might compel DC to be transmitted at 380 V, which would require a DC-DC conversion to step the voltage down to 50 V for small appliance use.

Electricity conversions. Due to the use of power electronics, converting electricity from one form to another typically occurs with an efficiency at peak load that is normally above 90%, and often above 95%, as discussed in section 1.1 and demonstrated below in Table 9.

Input Voltage	Output Voltage	Power	Symbol	Value	Used For
DC High	DC High	High	$e_{DC\text{-}DC}$	0.976	MPPT, Charge controller
DC High	DC Low	Low	$e_{sl,\ DC}$	0.960	DC bus to small loads
DC High	AC High	High	$e_{DC\text{-}AC}$	0.976	Battery or PV to AC bus
AC High	DC High	High	$e_{AC\text{-}DC}$	0.965	AC bus to large DC loads
AC High	AC Low	High	$e_{AC\text{-}AC}$	0.985	AC 480V-120V transformer
AC High	DC Low	Low	$e_{sl,\ AC}$	0.950	AC bus to small DC loads

Table 9: Representative peak load efficiencies for various electricity conversions used in the (Backhaus et al. 2015) study. Table adapted from Backhaus et al. 2015.

Thus, any significant energy efficiency difference between an AC and DC micro-grid used in the same environment will be highly dependent on the number of electricity conversions that are needed. In turn, the number of conversions is dependent on the specific implementation of the micro-grid, in particular, any backup grid connections and the use of energy storage.

Micro-grids with distributed renewable energy generation have a limitation because electricity is only available when the renewable sources are generating electricity: during daylight hours for solar and when the wind is blowing for wind turbines. A backup connection to the main AC grid is one way of ensuring that electricity is available when it is needed. Even if independent grids are not initially built with a backup grid connection, one might be planned for in the future as the grid expands. If an AC micro-grid has a backup connection to the central AC grid, then this connection would need to be phase-matched but no other electrical conversion would be necessary. A DC micro-grid with a backup AC connection would require an additional AC to DC electrical conversion.

Energy storage can also be used to mitigate the problem of intermittent renewable electricity generation. Since the most common local energy storage devices, batteries and fuel cells, are DC-native technologies, an AC architecture would require an additional AC-DC-AC conversion for energy storage and then energy extraction. A DC architecture would likely require only a DC-DC voltage conversion.

As seen in Table 10, Backhaus et al. demonstrate that the energy efficiency of AC vs. DC micro-grid architectures is dependent on design and thus the number of electrical conversions needed. As expected, modelling indicates that many configurations of DC systems are more efficient than their AC equivalents. In cases with backup grid connections however, (cases (a) and (b)), or backup diesel generators that generate AC power (Cases (e) and (f): firm generation), AC micro-grids may be more efficient than DC micro-grids.

Architecture	Load	Symbol	Value
a) AC network	M	$e_{DC-AC}-e_{al, AC}$	0.927
...	D	$e_{DC-AC}-e_{al, AC}$	0.927
b) DC network	M	$e_{DC-DC}-e_{al, DC}$	0.956
...	D	$e_{DC-DC}-e_{DC-AC}-e_{AC-DC}-e_{al, DC}$	0.901
c) AC μgrid, PV, Battery	M	$e_{DC-AC}-e_{al, AC}$	0.927
...	D	$e_{brt, AC}-e_{al, DC}$	0.860
c) DC μgrid, PV, Battery	M	$e_{DC-DC}-e_{al, DC}$	0.956
...	D	$e_{brt, DC}-e_{al, DC}$	0.887
e) AC μgrid, firm generation	M	$e_{al, AC}$	0.950
f) DC μgrid, firm generation	M	$e_{AC-DC}-e_{al, DC}$	0.946

Table 10: Results of the Backhaus et al. (2015) energy efficiency study of six reference 100 kW micro-grid architectures. Each grid architecture was tested using a matched load (M) where local generation perfectly matches energy demand, and a disjoint load (D), where peak local generation occurs at the times of lowest energy demand, so that the maximum amount of energy has to be stored before it is used. Table adapted from Backhaus et al. 2015.

DC micro-grids at 380 V are already being widely adopted for data centre use, and have demonstrated efficiency gains of between 8-10% over their previous architectures, which used standard AC mains electricity, because of the lower number of electricity conversions necessary to run the DC-native electronics (Oliver 2012).

DC-native appliances. LED lighting and electronics appliances are already DC-native technologies, so any efficiency gain from their use will come from fewer electricity conversions. However, as discussed in section 1.4.2, electrical motors may be designed for use with AC or DC electricity, or both. While the best AC and DC motors have similar efficiency at similar speeds, recent advances in variable speed drives (VSDs) have increased energy efficiency because they can vary the motor speed according to need, so, for example, a motor does not run faster than is needed at a particular time. VSDs typically convert DC electricity into a pseudo-AC waveform, and can vary the frequency of this pseudo-AC waveform in order to vary motor speed. Therefore, switching to VSDs which take a DC electricity input may have an energy efficiency advantage for certain applications where a fixed motor speed is not desirable.

Garbesi et al. (2011) conclude that switching from standard AC appliances to the most efficient DC appliances would result in substantial energy savings, as seen in Table 11. However, the energy savings in column (A) of Table 11 are not necessarily comparing like-for-like appliances because it is comparing standard AC appliances with the most efficient DC alternative appliance. The DC alternative considered may have other features (for example, better insulation for a freezer) which are transferrable to the AC appliance. However, this caveat does not change the conclusion that there are substantial potential energy savings from switching to DC appliances.

Appliance	(A) Energy savings from switching to DC-compatible run on AC	(B) Energy Sniings from avoided AC-DC power conversion losses
Lightning-Incandescent	73%	18%
Lightning-Reflector	71%	18%
Lightning-Torchiere Refrigerators	69%	18%
Freezers	53%	13%
Dishwashers	53%	13%
Electric Water Heaters	51%	12%
Electric Space Heaters other then Heat Pumps	50%	12%
Spas	50%	12%
Central Air Conditioners	50%	12%
Electric Clothes Dryers	47%	11%
Room Air Conditioners	45%	11%
Furnance Fans and Boilers	34%	11%
Circulation Pumps	30%	13%
Clothes Washers	30%	13%
Cealing Fans	30%	13%
Electric Cooking Equipments	12%	12%
Lightning-Flourescent	1%	18%
Home Audio	0%	21%
Personal Computers and Related	0%	20%
Rechargeable Electronics	0%	20%
DVDs/VCRs	0%	31%
Security Systems	0%	17%
Color TVs and Set-Top Boxes	0%	15%
Coffee Maker	0%	13%
Electronic Other	0%	13%
Microwave Ovens	0%	13%
Electric Heat Pumps	0%	12%
Geothemal Heat Pumps	0%	12%
Solar Water Heaters	0%	12%
Electric Heat Pumps	0%	12%
Geothemal Heat Pumps	0%	12%
Electric Secondary Space Heaters	0%	11%
Average savings (consumption weighted)	33%	14%

Table 11: List of energy savings in appliances from (A) switching to DC appliances but running them on an AC grid; and (B) *additional* energy savings from using these DC appliances on a DC grid, thereby avoiding the appliance-level AC-DC conversion. Adapted from Garbesi et al. (2011).

2.5.2. Reliability

The reliability of a micro-grid is a function of the number of power conversion devices in the design, the individual reliability of each power conversion device, and the criticality of each device to the overall functioning of the micro-grid. As discussed in section 2.5.1, the number of electrical conversions is highly dependent on grid design choices. In a micro-grid that is not connected to the AC main grid, the lower number of AC-DC electrical conversions in a DC distribution architecture with DC native appliances means that there are fewer points of potential equipment failure, and thus potentially a higher overall reliability given similar levels of reliability for individual electricity conversion devices and appliances.

In addition, DC distribution systems have an advantage over AC systems because they do not require frequency matching between multiple distributed generation sources and possibly a backup AC grid connection. Given the large number of design choices for micro-grids, Backhaus et al. (2015) conclude that the reliability of a micro-grid is actually a cost issue, as backup electrical conversion devices can increase grid reliability at increased capital cost. However, for off-grid systems with DC generation, DC energy storage, and no AC-grid connection, it may be reasonably concluded that a DC architecture in this situation would be more reliable than an AC architecture, due to the lower number of electrical conversion devices.

2.5.3. Capital cost

For a given set of electricity generation options, the capital costs of a standalone micro-grid system depend on (1) the cost of electricity conversion devices; (2) the cost of wiring; (3) the cost of appliances; and (4) the cost of installation. Several paper analyses are reviewed here, but this report has not found any well-documented cost studies of real-world DC micro-grids. The empirical studies that do exist, for example Groh et al. (2014), provide valuable evidence of energy efficiency savings in DC grids, but are limited in scope and do not necessarily directly compare equivalent AC and DC architectures.

Laudani and Mitcheson (2015) analyse these factors in a paper study of DC vs. AC electricity supply in UK office buildings, and find that a newly-installed DC system would have a capital cost of approximately 10% less than a comparable newly-installed AC system. However, the applicability of these results to off-grid systems may be limited because of the difference in application, as well as the simplifying assumptions made in this study. There are many pioneer firms, such as SOLShare[32], that are attempting to design new architectures for off-grid applications for both DC and AC micro-grids (SOLShare 2016). Architectures such as these may reduce system cost and allow for scalability as off-grid electricity consumption increases.

Backhaus et al. (2015), in their scoping study of a number of different DC micro-grid configurations, analyse and compare the costs for power electronics, wires, communication, and control systems for DC and AC micro-grids. They conclude that the capital cost for DC vs. AC micro-grids will be dominated by the cost of power electronics and electricity conversion, and thus will be highly dependent on the system options discussed in section 2.5.1. Also, DC architectures do not provide a significant advantage over AC architectures for grid communication. Although the difference is not quantified, DC micro-grids may have some cost advantage over their AC counterparts in the cost of control and protection systems because the fast response to changes in the constant-voltage DC system may lead to more uniform, and therefore less costly, system designs between micro-grids.

The capital costs of both DC and AC micro-grids may be improved in the future through (1) ad-

---

[32] *http://www.me-solshare.com/product/#nanogrid*

vances in technology which drive efficiency and cost improvements; and (2) economies of scale which allow advanced, energy efficient technologies to be produced at lower costs.

2.6 Future market penetration for DC appliances and systems

An assessment of the market potential for DC micro-grids with DC appliances begins with an assessment of the number of people without access to consistent grid-based electricity. The International Energy Agency defines electricity access for rural households to be below 250 kilowatt-hours per year and 500 kWh per year for urban households (International Energy Agency 2015a). The calculation assumes five people per household. For reference, 250 kWh per year is enough for use of a floor fan, mobile telephone, and 2 fluorescent light bulbs, each used for five hours per day. Based on this definition, the population without electricity access is defined in Table 12.

Region	Population without electricity access (millions)	Electrification rate	Urban electrification rate	Rural electrification rate
Developing countries	1,200	78%	92%	67%
Africa	635	43%	68%	26%
North Africa	1	99%	100%	99%
Sub-Saharan Africa	634	32%	59%	17%
Developing Asia	526	86%	96%	78%
China	1	100%	100%	100%
India	237	81%	96%	74%
Latin America	22	95%	98%	85%
Middle East	17	92%	98%	79%
Transition + OECD economies	1	100%	100%	100%
World	1,201	83%	95%	70%

Table 12: Global electricity access in 2013, as defined by the International Energy Agency. Adapted from International Energy Agency 2015b.

The International Renewable Energy Agency predicts that, without major new interventions, the number of Africans without electricity access may increase to 700 million by 2030 from 635 million in 2015 (IRENA 2016) because population growth will outstrip new connections to the electrical grid. This group may gain access through either an extension of the main grid or through local micro-grids. Though the provision of electricity with micro-grids supplied by renewable energy is often considered to be the ideal solution for off-grid electricity access, the International Renewable Energy Agency (IRENA) has found that the share of renewable energy has been falling in developing countries, due in part to low fossil fuel prices (IRENA 2016).

The data on the current penetration of off-grid renewable energy systems is limited. IRENA estimates, based on limited data, that there are six million solar home systems globally, of which three million are in Bangladesh (Kempener et al. 2015). However, the definition of a solar home system is quite wide, and includes systems which may provide only enough electricity for minimal lighting and mobile phone charging, as well as systems that meet the more robust IEA definition of electricity access.

The data in Table 12 may undercount the potential market for DC micro-grids for two reasons. First, some of those households counted by the IEA as having electricity access may have limited electricity resources, either because of an unreliable grid connection or because they contain a number of small home appliances. Second, as has been demonstrated to a limited extent in data centres and buildings in developed countries, DC micro-grids connected to DC generation and DC appliances may demonstrate enough energy efficiency benefit to justify replacing AC distribution infrastructure with DC systems.

The current market penetration of micro-grid sized DC electrical systems is unknown. As shown in Figure 16, Navigant Research estimate that for "nano-grids" as defined by Navigant—systems serving a single load or building, that is 100 kW for grid-tied systems and 5 kW for remote systems not interconnected with a utility grid—total vendor revenue is set to grow 50% by 2023, with most of the growth occurring in the Middle East, Africa, and Asia Pacific regions.

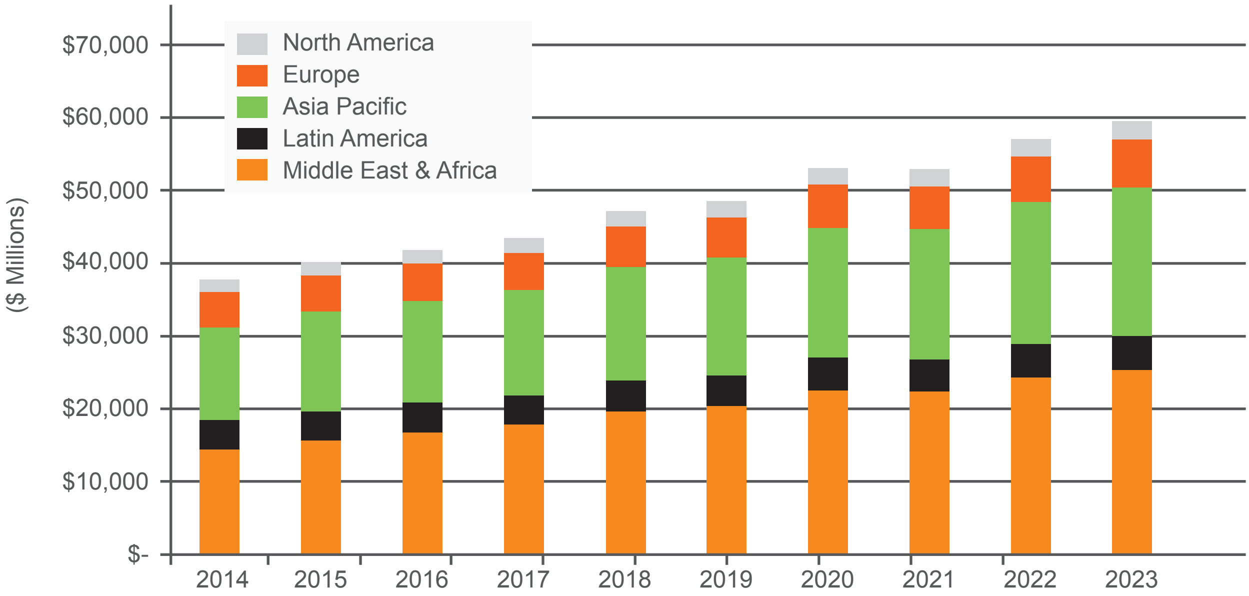


Figure 16: Projected growth in nano-grid (as defined by Navigant Research – see above) vendor revenue through 2023 Asmus and Lawrence 2014.

For DC micro- and nano-grids in particular, Asmus and Elberg (2015) define four key markets in their 2015 report: (1) telecommunications towers; (2) data centres; (3) grid-connected commercial buildings; and (4) off-grid military networks. This leaves out the crucial village-level micro-/nano-grid off-grid market, that may provide large growth in the future though. The projected growth for the latter four of these segments is shown in Figure 17. Although this report does not specifically address off-grid communities and homes, the lack of growth in projected revenues for DC grid implementation in Africa and Latin America is indicative of a negative perspective on the growth potential of DC micro-/nano-grids in these regions.

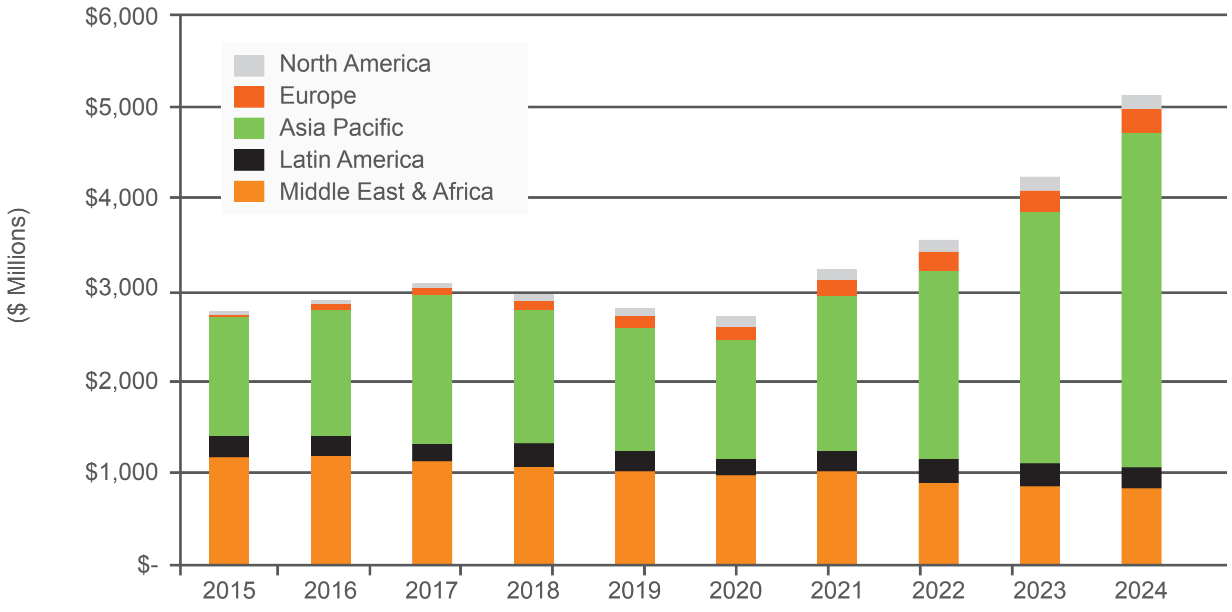


Figure 17: DC distribution network implementation revenue for a base scenario. Adapted from Asmus and Elberg 2015.

In an updated report to Asmus and Lawrence 2014, Asmus and Dehamna (2015) examine the future of nano-grids with solar PV generation plus energy storage capacity. As seen in Figure 18, they project that the market for this type of installation, agnostic as to whether the nano-grids and loads are AC or DC, will experience large global growth rates through 2024. As section 2.5 discussed, micro- and nano-grids supplied by solar PV and with DC-native energy storage represent a design case where a DC architecture may have significant energy efficiency advantages over an AC architecture. Thus, it is reasonable to assume that a significant portion of this growth may be in DC or hybrid AC-DC systems.

However, Figure 18 is notable for the small fraction of the global solar nano-grid plus storage market from Africa or Latin America. Asmus and Dehamna (Asmus and Dehamna 2015) assert that Africa has 3.7 MW of installed capacity as of 2015, which under their base scenario expands to 62 MW by 2024, an annual growth rate of approximately 37%. Latin America has 2.5 MW of installed capacity in 2015, which expands to 113 MW by 2024, an annual growth rate of 53%. Those these regions have high annual growth rates, they are starting from a very small installed capacity.

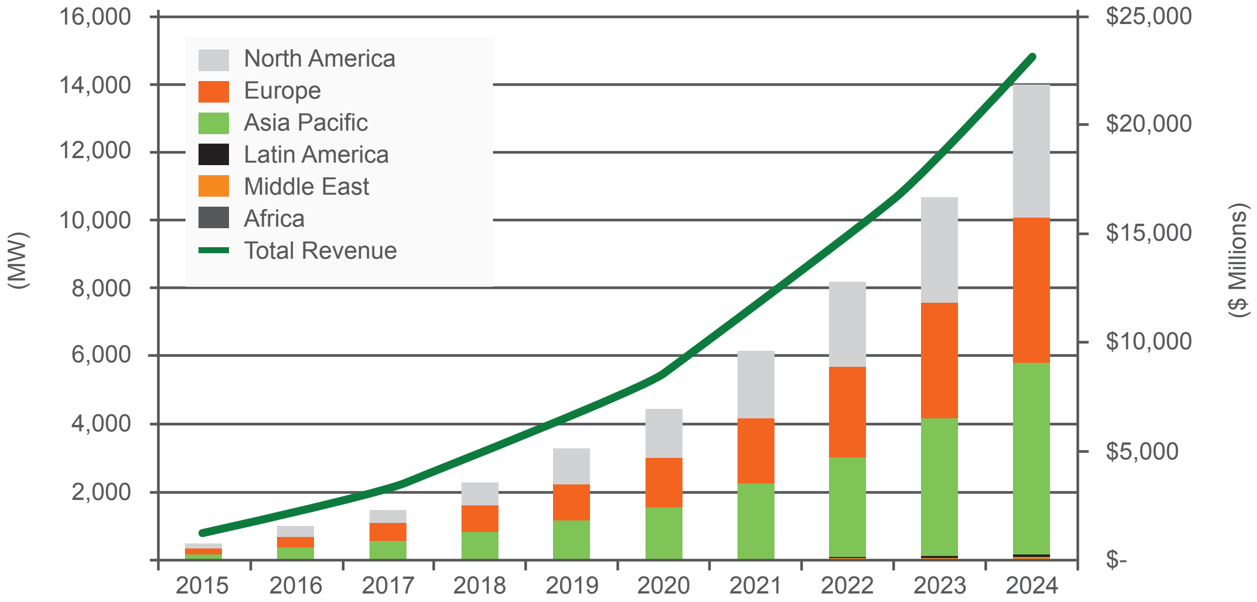


Figure 18: Nano-grid (as defined by Navigant Research[26]) solar PV plus energy storage capacity, broken down by region. Figure adapted from Asmus and Dehamna 2015.

Despite the growth in the availability of DC appliance designs, as seen in the GIZ catalogue (GIZ 2016), those in traditional micro-grid markets estimate global market share of DC components not to grow very much in the medium term. However, the large and increasing uptake of solar home systems, particularly in Bangladesh and East Africa, may provide a significant impetus for increased energy efficiency in standard household appliances, necessitating the manufacture of more native DC products, such as fridges, fans, sewing machines, etc. How much this increase in solar home systems affects uptake of DC appliances depends on several factors. As we have discussed elsewhere, the ability to standardise systems, upsize individual solar home systems, and link up solar home systems between homes (as is being done in Bangladesh to create extra capacity for end uses beyond lighting and mobile phone charging) will be a crucial factor in determining whether solar home systems provide a "push factor" for increased market penetration of DC appliances.

Of the fundamental components listed in Table 2, DC-native lighting (LED), electronics, and energy storage components are expected to experience very high market growth rates in the next ten years. Both AC and DC electric heating element technology is already mature.

Figure 19 shows projections for the future market size for low-voltage electrical motors, where DC motors are expected to make up less than 1% of the market in the future. AC electric motors are still far more common than DC electric motors in non-mobile, mains-powered applications, and, as Figure 19 indicates, this is not expected to change in the near term. The DC motor market may experience high annual growth rates if much of the growth in nano-grid solar PV plus energy storage capacity, seen in Figure 18, uses DC rather than AC architectures.

---

33 100 kW for grid-tied systems and 5 kW for remote systems not interconnected with a utility grid.

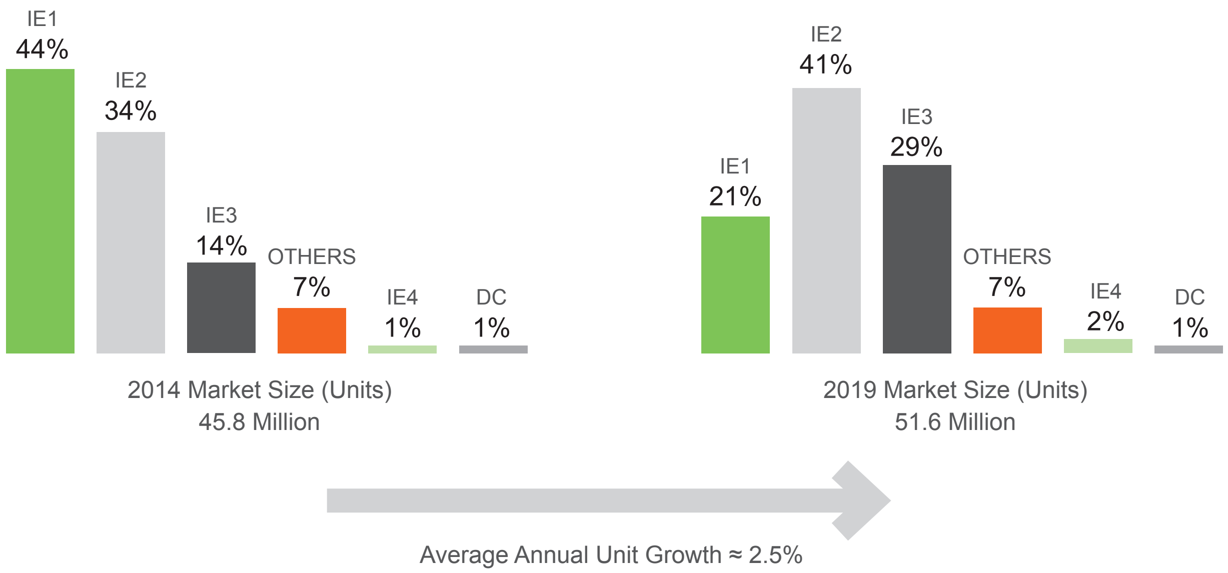
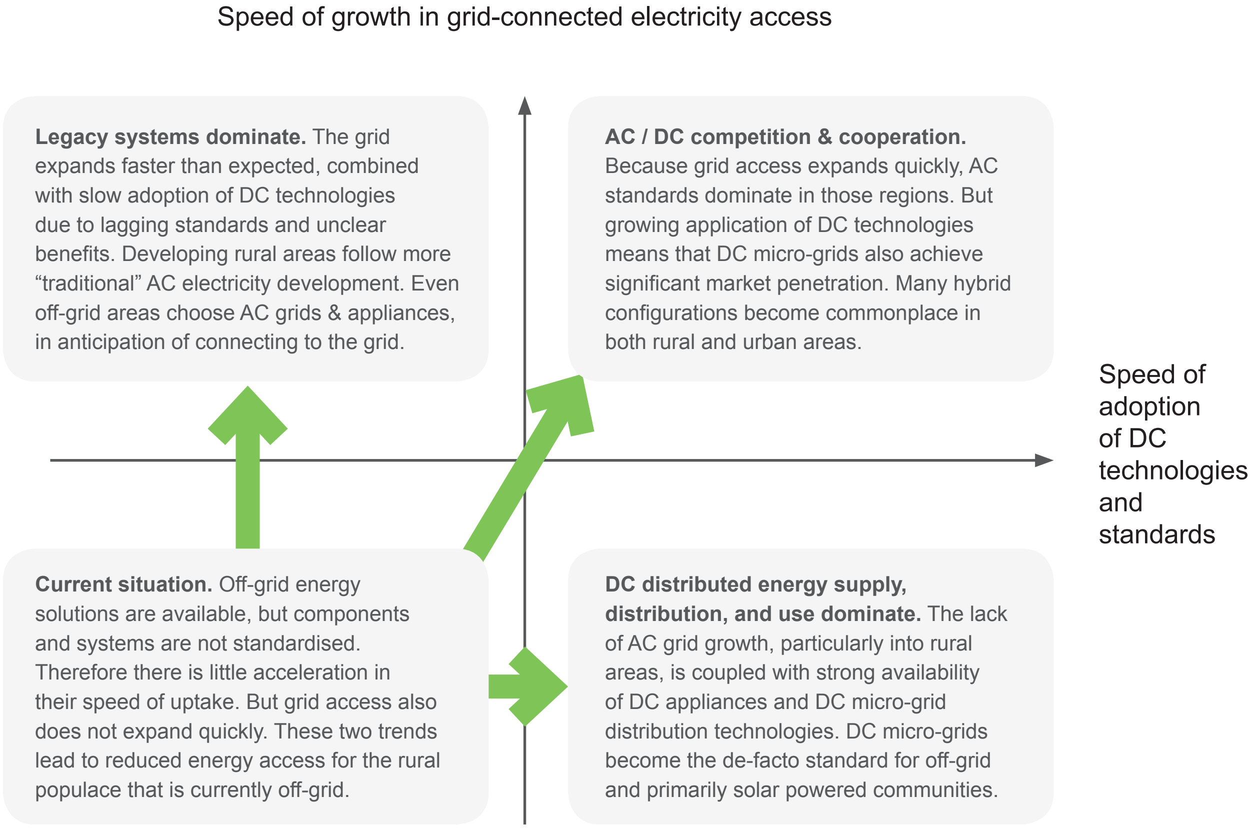


Figure 19: Projections on the market size and split for the low-voltage (<1000 V) motor market (IEA 2015). IE1, IE2, IE3, and IE4 designations refer to standard, high efficiency, premium efficiency, and super premium efficiency classes of AC electric motor, respectively.

The current and projected market size for DC motors may be an indication that international motor manufacturers do not yet consider that the DC micro-grid market is large enough to justify the large scale production of DC motors and appliances. Conversely, the lack of production of such motors (and the appliances that contain them) may influence end users to install AC rather than DC micro-grids.

In the next 10 years, the market penetration of DC appliances and distribution systems may evolve according to two key uncertainties. The first uncertainty is the speed of adoption of DC energy supply, storage, and appliance technologies. The second uncertainty is the speed of growth in grid electricity access to remote communities. Figure 20 describes potential scenarios based on these two uncertainties.



Legacy systems dominate. The grid expands faster than expected, combined with slow adoption of DC technologies due to lagging standards and unclear benefits. Developing rural areas follow more “traditional” AC electricity development. Even off-grid areas choose AC grids & appliances, in anticipation of connecting to the grid.

AC / DC competition & cooperation. Because grid access expands quickly, AC standards dominate in those regions. But growing application of DC technologies means that DC micro-grids also achieve significant market penetration. Many hybrid configurations become commonplace in both rural and urban areas.

Current situation. Off-grid energy solutions are available, but components and systems are not standardised. Therefore there is little acceleration in their speed of uptake. But grid access also does not expand quickly. These two trends lead to reduced energy access for the rural populace that is currently off-grid.

DC distributed energy supply, distribution, and use dominate. The lack of AC grid growth, particularly into rural areas, is coupled with strong availability of DC appliances and DC micro-grid distribution technologies. DC micro-grids become the de-facto standard for off-grid and primarily solar powered communities.

Figure 20: Matrix showing four possible future scenarios of DC micro-grid growth, based on the key uncertainties of (1) the speed of growth in off-grid electricity access; and (2) the speed of adoption of DC technologies and standards.

As reflected in the matrix in Figure 20, the extent of adoption of DC grid architectures and appliances for off-grid homes and villages is dependent on how quickly DC technologies and standards are available at any given location, versus the speed of growth in main grid electricity access. Because both AC grid architectures (main grid and micro-grid) and standalone appliances are already widely available, any given location must have available technology, incentives, and pathways for choosing a DC architecture. As a result, instances of successful micro-grids to date typically use an AC architecture. In the Bunker et al. (2015) survey of ten leading renewable micro-grid implementations, all use AC distribution technology. In general, it appears that communities with legacy diesel generation systems are likely to keep their AC grid and appliance systems. The EMerge Alliance maintains an up-to-date list of implementations of their DC standard, and to date (May 2016), all of these implementations are found in the United States.[34]

---

[34] *http://www.emergealliance.org/Products/DemonstrationSites.aspx*

CONCLUSIONS

Increased access to a stable and sufficient supply of electricity in rural communities in developing countries will be achieved from a combination of: (1) AC grid access; (2) AC micro-grids supplied principally by distributed electricity generation; (3) DC micro-grids supplied principally by distributed electricity generation; and (4) solar home systems and stand-alone PV appliances for productive uses.

Evidence on the availability of native DC appliances indicates that it is now feasible to procure the components for all-DC home electrical systems. DC micro-grids connected to DC appliances offer energy efficiency and cost advantages in many off-grid situations, resulting in enhanced energy access for those who currently lack sufficient access to electricity.

However, the following three barriers may impede the adoption of DC micro-grids in any given locale, and each of these barriers is explored further in section 3.3:

1. Local energy supply options may favour AC generation, for example through micro-hydro generation, or combustion engines, or there may be insufficient solar resource in a given location, leading to adoption of AC systems rather than DC systems. However, if the solar resource is good, the capability to supply DC power through solar PV will significantly increase the appeal of DC over AC architectures.

2. The manufacturers of DC appliances, energy storage, and distributed energy generation systems are often companies seeking to address global markets. But DC distribution, conversion, and appliance technology may not be available in a given locale, or they may be more expensive than alternatives at the time when off-grid households have the capital available to finance electricity access.

3. Global standards for the design and installation of DC micro-grids may not be adopted locally and local expertise for their design, installation, and use may not be available.

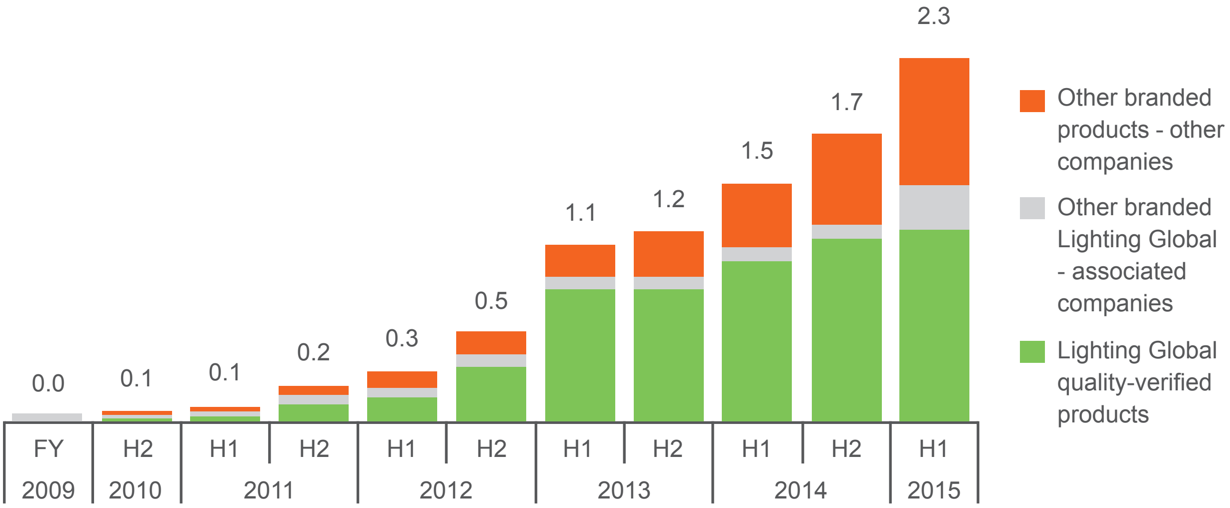
Policymakers at the national or regional level can actively encourage the development of DC micro-grids through the adoption of relevant standards, training programmes, and procurement programmes.

3.1. Competing technologies

As alternatives to DC micro-grids, off-grid households and communities may also seek to expand their access to electricity through either AC micro-grids or AC grid growth. While this report has already addressed the advantages and disadvantages of AC and DC micro-grids, AC grid growth options will also have a significant role in expanding electricity access. For example, the IEA estimates that in sub-Saharan Africa, 48% of those who currently lack electricity access would be best served through extensions of the grid, 18% with standalone systems, and 34% from micro-grids (IEA 2014).

3.1.1. Stand-alone appliances and solar home systems

As has been stated earlier in the report, solar home systems, pico-solar lanterns, and standalone appliances for productive energy use, have seen significant recent market expansion, and their growth in the future is likely to spur on the adoption of other DC appliances. This is exemplified in the sales data for solar lanterns in Asia in Figure 21. The market for pico-solar lanterns and solar home systems has been growing rapidly. For example, Kempener et al. estimate that between 20-28 million solar lanterns are operating in Africa alone, with current sales of approximately 6-10 million per year (2015).



Source: Bloomberg New Energy Finance, Lighting Global, GOGLA. Note: Figures are reported to Lighting Global and GOGLA with additional BNEF estimates for missing data points and other branded sales.

Figure 21: Sales of branded pico-solar lighting products in Asia (millions of units). Figure adapted from Lighting Global 2016.

These trends suggest very positive outcomes for future growth in DC appliances and electricity distribution systems. These solar home systems and pico-lights are only mentioned here as a “barrier” to DC adoption due to the small potential that under the wrong conditions, rural consumers could get “stuck” on the energy ladder. This could occur through sales of bad quality lighting and small-scale energy distribution products, leading to distrust and lack of desire for larger and more useful DC electric systems. Also, if the technological and business model aspects of solar home systems are not designed to be flexible and easily upgradeable, there is concern that consumers may remain in a very low level of energy consumption, even after a relatively high level of capital expenditure for individual households.[35] However, there is good evidence that many companies are well aware of these pitfalls, and are actively seeking ways to advance rural consumers up the energy ladder with DC appliances and energy distribution systems. This seems more likely to provide a positive impetus for adoption of DC technologies than to act as a barrier.

Some industrial and commercial appliances come integrated with a fossil fuel generator for a power source. Schultz et al. (2013), in their study of the productive use of energy in Indonesia, reported that these appliances were in some cases preferred to appliances on the newly installed micro-grid because of their portability and reliability. These appliances will be AC, and thus will compete directly with DC appliances.

It is clear that standalone appliances will be a significant class of appliances for households and villages climbing the energy ladder (Scott and Miller 2016). Whether current and future capital spending on these types of appliances will delay investment in micro-grids is an uncertainty in the extent to which DC architectures will be adopted.

---

[35] *http://e360.yale.edu/feature/african_lights_microgrids_are_bringing_power_to_rural_kenya/2924/*

3.1.2. AC grid growth

Particularly in peri-urban areas, growing the AC grid while making it more reliable is a viable option for increasing electricity access. For example, Ghana has increased electricity access through the Self-Help Electrification Programme, which aims to connect all communities within 20 km of the existing electricity grid and had connected 2,837 communities through 2009 (Scott 2015). Uncertainty about the future of AC grid growth can contribute to a reluctance to invest in micro-grids, as has been discovered in India.[36]

3.2. Off-grid energy demand trends

The choice between these technologies—AC micro-grids, DC micro-grids, solar home systems with standalone appliances, and grid connections—depends in part on how electricity demand evolves in households and communities that are currently off-grid. Generally, reliable central grid connections will have the capacity to meet greater levels of electricity demand, followed by AC or DC micro-grids, while standalone appliances are less capable of meeting growing electricity demand because they consist of dedicated power sources for each appliance.

As noted in this report, many current DC appliances are built as standalone with an attached PV module and perhaps energy storage. The most numerous examples of pico-grids today are solar lanterns, of which tens of millions have been sold,[37] though examples of refrigerators and other appliances exist (GIZ 2016). However, total energy demand is set to rise in off-grid households. For reference, the average annual electricity usage in a United States household is currently 11,000 kWh per year, or approximately 30 kWh per day.[38] In Europe, this figure is between 4,000-5,000 kWh per year, or approximately 12 kWh per day. Grid-connected households in developing countries typically use between 3 and 6 kWh per day (World Energy Council 2015). In contrast, the current electricity usage in off-grid villages is much more variable, ranging from 0 to 10 kWh per day.

Sanjeev et al. (2015) find that a typical Indian household on DC power with efficient LED lighting, a DC fan, and a DC TV might use approximately 1 kWh per day, while a typical grid-connected AC household with incandescent lighting, and AC fan, and a standard TV might use around 4 kWh per day. The DC household is more efficient, though the data does not allow us to directly compare the level of service delivered in these two households. However, it is expected that at some point the off-grid DC household will still desire an increased amount of power on levels comparable with the AC grid. If the economies of rural villages continue to develop, household electricity use may rise to the current level of grid-connected households in the same country.

Furthermore, electrical loads may represent an increasing share of total household energy use in off-grid homes, as electronics, electric lighting, and electric motors become more widespread. Further into the future, large energy demand centres such as electrified transport may become options for off-grid communities as prices decrease and concerns about local air pollution from internal combustion engines become more widespread. A report by *Bloomberg New Energy Finance* predicts that electric vehicles may become cost competitive with internal combustion engines in the 2020s[39], which could drive demand for such transportation in off-grid as well as on-grid locations. The Tata eMo, a small concept electric vehicle, has a range of 160 km with an 18.4 kWh battery (Tata Technologies). Taking into account charging losses of 15%, the discharge and recharge of one of these

---

[36] *http://e360.yale.edu/feature/in_rural_india_solar-powered_microgrids_show_mixed_success/2948/*

[37] *https://www.ashden.org/solar*

[38] *https://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3*

[39] *http://about.bnef.com/press-releases/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/#_ftn1*

vehicles once per week would add an electricity demand of approximately 3 kWh per day to an off-grid household. Anecdotal evidence suggests that electric bicycles ("e-bikes") are becoming popular in rural, off-grid settings. Though e-bikes have a lower level of electricity consumption than electric automobiles, they may still represent a significant future electricity demand.

In on-grid systems, it has been customarily assumed that electricity is available at the time and place that it is needed. Under this assumption, it is the responsibility of the electricity generator to ensure that the supply and demand on the grid stay balanced so that the grid maintains a stable frequency in order to prevent blackouts (a complete disruption of electricity supply) or brownouts (a reduction in the voltage of electricity supply). However, energy demand management, where at least some of the responsibility for maintaining the supply/demand balance is shifted to the electricity consumer, is becoming more popular for three reasons: (1) it is often cheaper to pay someone not to use electricity during peak use times than to pay to generate more electricity; (2) modern IT technology allows for individual appliances to be shut off or throttled in response to grid stress; and (3) the increasing penetration of intermittent renewable electric generation means that the supply of electricity is more variable and cannot be easily throttled without electricity storage. For off-grid AC or DC micro-grid systems using renewable energy as their primary electricity supply, energy demand management is of great importance.

3.3. Barriers to adoption of DC micro-grids and appliances

The following three barriers will determine if DC micro-grids connecting distributed generation and DC appliances are the technology of the future.

3.3.1. The local context

This report has demonstrated that, while DC micro-grid architectures may deliver energy efficiency benefits, thus increasing the services provided by a given amount of distributed renewable electricity generation, such benefits are partly dependent on the local context. A DC micro-grid that does not have a backup grid connection, and has only solar-powered generation which is DC-native in an area of high solar insolation will likely have benefits over an AC architecture. Conversely, for a situation where a backup grid connection may be made at some point, or where distributed electricity generation comes in part from a diesel generator, wind, or water turbine, an AC architecture may be preferred over a DC architecture.

It may be that DC architectures will only be preferred in a limited range of local contexts, limiting the potential market size for DC grid equipment and appliances. Thus, with smaller market sizes and economies of scale, the capital costs of DC equipment may not decrease to match AC equipment costs.

3.3.2. Capital costs and availability

The availability, cost, and use of DC appliances are related: if relatively few DC micro-grids are implemented then the market for DC equipment and appliances will be limited, thus preventing economies of scale from reducing costs for these products. The upfront capital costs of electrical micro-grids, whether AC or DC, are significant for consumers, the majority of which may not have access to traditional banking and credit services.

Until recently, the business market for DC appliances was largely restricted to mobile (car, truck, train, ship, and plane) applications. The catalogue of DC appliances published by GIZ, "Photovoltaics for Productive Use Applications" (GIZ 2016), documents DC appliances specifically designed for business use (rather than domestic use) in off-grid environments. The mobile market, as well as the developing off-grid market, means that DC appliances for specific off-grid applications are available, somewhere in the world, at some price point. This is particularly true for low power appliances, such as lighting, radios, mobile phone chargers, and televisions. However, the availability of specific appliances in specific locales, built to local voltage and safety standards with standardised electrical plugs, good quality construction, and sold at competitive prices, has not yet been realised. Many of the appliances listed in, for example, the GIZ catalogue or EMerge approved suppliers list, are not available globally, particularly not in developing markets. This lack of availability is primarily due to a lack of a global supply chain and distribution system for such appliances.

The report by van Gevelt and Holmes (2015), "Business models for home-based electricity services", documents a number of business models for increasing the availability of appropriate DC appliances to off-grid households and businesses. Currently, many of the low-power appliances used with solar home systems are provided by the seller of the solar home system itself. Other possible models for increasing the availability of DC appliances include standard distributor-dealer channels, and partnerships with institutions with pre-existing linkages to customers.

Van Gevelt and Holmes (2015) note that a number of pioneer firms have made progress in delivering pico-solar lighting systems and solar home systems, but that multi-national corporations have not yet made the investments into these distributed electricity systems to help standardise products and their distribution channels. Improving the global distribution of standardised and certified DC appliances and electrical equipment will likely decrease appliance costs. Given the potential size of the addressable market for DC appliances, the global availability of DC appliances may be significantly improved by 2025, so long as common appliance voltage standards are adopted.

DC appliances that are designed to operate in the off-grid environment are typically designed to be as energy efficient as possible, given the power supply constraints of solar home systems or other off-grid energy supply technologies. However, devices with high energy efficiency are normally costlier to purchase, due to the inclusion of more efficient but expensive components. For example, the Clean Energy Ministerial (2016) report on the future market for off-grid televisions, refrigerators, and fans documents that refrigerators designed for off-grid use are significantly more expensive than similarly-sized AC refrigerators due to DC refrigerators' use of variable-speed brushless DC motors. There is a 10-year payback period on the DC refrigerator's superior energy efficiency, compared to less expensive AC refrigerators. Prices for more energy-efficient DC refrigerators are expected to decrease with volume production, but this depends on the development of the market.

Furthermore, without regulatory pressure from governments, market inefficiencies may prevent energy efficient products with the lowest lifecycle cost from being available in off-grid situations. High efficiency appliances will have larger capital costs, potentially incentivising manufacturers to introduce less efficient, lower capital costs appliances to off-grid consumers. These consumers may not have the necessary information to differentiate between high efficiency and low efficiency appliances. While this market inefficiency has been addressed via regulatory standards in North America and Europe, it is unknown to what extent similar standards might be adopted in regions with a high percentage of off-grid consumers. The Global LEAP programme, has identified that "the proliferation of low quality, cheap products currently inhibits the market for off-grid appliances; well designed and enforced quality control frameworks will support growth" (Clean Energy

Ministerial 2016). The Global LEAP program created a data sharing initiative in 2015 to facilitate the development of policies which encourage the sale of energy efficient appliances.[40]

3.3.3. Standards, regulatory, and business barriers

As seen in Table 7, there are a number of emerging DC distribution standards that address design, installation, and safety concerns. AC grid standards are well established, and equipment, appliances, and training regimes are in place to follow these standards. Conversely, pico-grids, as self-contained systems, do not necessarily require the standards and regulations that would be required for standardised DC micro-grids.

Scott and Miller (2016), in their report "Accelerating access to electricity in Africa with off-grid solar", provide a framework for specific government support needs to increase off-grid electricity access: (1) off-grid is specifically included and well-implemented in national energy policy; (2) there is low value-added tax (VAT) and import tariffs on solar products and other electrical equipment; (3) the government takes steps to ensure off-grid market readiness; (4) the country has a high "ease of doing business" ranking; and (5) there are nationally adopted quality standards in line with global standards. Support needs (2), (3), and (4) are specifically about creating an attractive investment environment for off-grid energy.

The implementation of DC micro-grids will require that the national energy policy is specifically supportive of DC technologies and standards. While developed economies, such as the United States, have actively developed standards and tax policies to encourage DC micro-grids (Savage et al. 2010), these developments have generally been slower in developing economies (Brüderle et al. 2012). Furthermore, support for training in the installation and maintenance of DC systems will be relatively more important in developing economies.

3.4. Future research on DC micro-grids

The progress of the off-grid community and household DC electrical systems will be dependent on overcoming the barriers of local context, capital cost, and standards, whilst the development of the central grid, AC micro-grids, and standalone and solar home systems continue to increase consumers' options.

In 2016, the known implementations of DC micro-grids are primarily in data centres in developed countries. The theoretical analyses of DC micro-grid efficiency advantages for off-grid use indicate that DC micro-grids may possess advantages to alternatives. Demonstration projects for off-grid DC systems are clearly needed to understand their benefits under real-world conditions.

In addition, to help stimulate global demand for DC micro-grid components, there are two distinct packages of further work to study and influence the evolution of DC electrical systems. First, market studies on the future demand for, and availability of, DC appliances may be conducted in collaboration with manufacturers of those appliances. The data on the number, capacity, and location of installed micro-grids worldwide, either AC or DC, is poor.[41] Though the global market for DC micro-grid components is maturing, studies on the number of installed micro-grids, and the regional and local barriers to adoption of these systems would illuminate particular interventions that might speed the adoption of these systems in off-grid areas. Furthermore, an analysis that determines where off-grid houses and communities are, the distance from the electricity grid, the local energy generation potential, and the local

---

[40] *http://www.cleanenergyministerial.org/News/global-leap-climateworks-and-clasp-spearhead-groundbreaking-energy-access-program-47026*

[41] *http://e360.yale.edu/feature/african_lights_microgrids_are_bringing_power_to_rural_kenya/2924/*

regulatory context would allow for a determination, at a very fine level, of the potential market size for DC micro-grids.

Second, engineering modelling work on household DC electrical systems would better inform both engineers and consumers on how they might match energy supply and demand as the efficiency and cost of energy supply, transformation, and demand change over time. Given the conclusion that a substantial portion of the energy efficiency benefits of DC micro-grids over AC micro-grids might disappear if AC grid connections are required to supply additional electricity to micro-grid enabled communities, the balance between electricity demand, as incomes and technologies change, and off-grid energy supply is essential to the choice of building AC or DC micro-grids.

BIBLIOGRAPHY

Active Power. *Operation and Performance of a Flywheel-Based Uninterruptible Power Supply (UPS) System*. http://www.activepower.com/.

Alstone, P., D. Gershenson, and D.M. Kammen. 2015a. Decentralized energy systems for clean electricity access. *Nature: Climate Change* 5(2002): 305–314. http://dx.doi.org/10.1038/nclimate2512.

Alstone, P., D. Gershenson, N. Turman-Bryant, D.M. Kammen, and A. Jacobson. 2015b. *Off-Grid Power and Connectivity: Pay-as-you-go Financing and Digital Supply Chains for Pico-Solar*. Berkeley, CA. https://www.lightingglobal.org/wp-content/uploads/2015/05/Off_Grid_Power_and_Connectivity_PAYG_May_2015.pdf.

Asmus, P. and A. Dehamna. 2015. Executive Summary: Solar PV plus Energy Storage Nanogrids Grid-Tied Systems for Residential and Commercial Applications: Market and Technology Issues, Industry Profiles, and Global Market Forecasts.

Asmus, P. and R. Elberg. 2015. *Executive Summary: Direct Current Distribution Networks Data Center , Commercial Building , and Military Applications*.

Asmus, P. and M. Lawrence. 2014. *Executive Summary: Nanogrids: Grid-Tied and Remote Commercial, Residential, and Mobile Distribution Networks: Global Market Analysis and Forecasts. Navigant Research*.

Backhaus, S., G.W. Swift, S. Chatzivasileiadis, W. Tschudi, and S. Glover. 2015. *DC Microgrids Scoping Study — Estimate of Technical and Economic Benefits*.

Bertényi, T. and T. Young. 2009. Power electronics solutions for vertical axis urban wind turbines. *2009 IEEE Electrical Power and Energy Conference, EPEC 2009*: 1–7.

Boeke, U. and M. Wendt. Comparison of low voltage AC and DC power grids: 1–4. http://www.upn.se/html-files/Glava/Referenser/Ref 1 Boeke-Comparison_of_low_voltage_AC_and_DC_power_grids.pdf.

Brüderle, A., B. Attigah, and M. Bodenbender. 2012. *Productive Use of Energy – PRODUSE A Manual for Electrification Practitioners*. Berlin.

Bunker, K., S. Doig, K. Hawley, and J. Morris. 2015. *Renewable Microgrids: Profiles from Islands and Remote Communities Across the Globe*. Boulder, Colorado. WWW.RMI.ORG/ISLANDS_RENEWABLE_MICROGRIDS.

Carannante, G., C. Fraddanno, M. Pagano, and L. Piegari. 2009. Experimental performance of MPPT algorithm for photovoltaic sources subject to inhomogeneous insolation. *IEEE Transactions on Industrial Electronics* 56(11): 4374–4380.

Clean Energy Ministerial. 2016. *The State of the Off-Grid Appliance Market*. http://cleanenergyministerial.org/Portals/2/pdfs/Global_LEAP_The_State_of_the_Global_Off-Grid_Appliance_Market.pdf.

Elserougi, A., A. Abdel-khalik, A. Massoud, and S. Ahmed. 2012. Flywheel Energy Storage System Based on Boost DC-AC Converter 6: 1725–1732.

EMerge Alliance. *DC Microgrids: Advanced Power Distribution Platforms for Flexibility, Savings*

& Sustainability in Buildings. San Ramon, CA. http://www.emergealliance.org/About/Vision.aspx.

European Telecommunication Standards Institute. 2011. ETSI EN 300 132-3-1 1: 1–31.

Feldman, D., R. Margolis, D. Chung, R. Fu, C.D. Nrel, G. Barbose, M. Bolinger, J. Seel, R. Wiser, and L. Berkeley. 2015. Photovoltaic System Pricing Trends - Electricity Market and Policy. Presentation. Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/all/files/pv_system_pricing_trends_presentation_0.pdf.

Fleiter, T., W. Eichhammer, and J. Schleich. 2011. *Energy efficiency in electric motor systems: Technical potentials and policy approaches for developing countries*. http://www.unido.org/fileadmin/user_media/Services/Research_and_Statistics/WP112011_Ebook.pdf.

Garbesi, K., V. Vossos, and H. Shen. 2011. *Catalog of DC Appliances and Power Systems*. http://efficiency.lbl.gov/publications/catalog-dc-appliances-and.

Gevelt, T. van and J. Holmes. 2015. *Business models for home-based electricity services Technical Report 4*. Cambridge, UK. http://e4sv.org/wp-content/uploads/2015/12/TR04-Business-models-for-home-based-electricity-services.pdf.

GIZ. 2016. *Photovoltaics for Productive Use Applications: A Catalogue of DC-Appliances*. https://energypedia.info/wiki/File:GIZ_(2016)_Catalogue_PV_Appliances_for_Micro_Enterprises.pdf.

Groh, S., D. Philipp, B.E. Lasch, H. Kirchhoff, D. Islam, M.R. Khan, S. Chowdhury, and D.M. Kammen. 2014. The Battle of Edison and Westinghouse Revisited : Contrasting AC and DC microgrids for rural electrification Functionality of DC microgrids. *MES-BREG 2014: Innovating Energy Access for Remote Areas: Discovering Untapped Resources*(October 2015): 1–8. https://www.researchgate.net/publication/268209879_The_Battle_of_Edison_and_Westinghouse_Revisited_Contrasting_AC_and_DC_microgrids_for_rural_electrification.

Holmes, J., B. Jones, and B. Heap. 2015. *Smart Villages: New Thinking for Off-Grid Communities Worldwide*. Ed. by Brian Heap. *Science*. Vol. 350. Cambridge, UK: Banson / Smart Villages Initiative. http://e4sv.org/wp-content/uploads/2015/07/Smart-Villages-New-Thinking-for-Off-grid-Comunities-Worldwide.pdf.

IEA. 2014. Africa Energy Outlook: 1–237. https://www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf.

IEA. 2015. *Energy efficiency roadmap for electric motors and motor systems*.

IEEE. *The Smart Village Initiative*. ieee-smartvillage.org.

IEEE. *SunBlazer II*. ieee-smart-village.org.

International Electrotechnical Commission. 2005. *Technical Specification TS 60479-1: Effects of Current on human beings and livestock*. https://webstore.iec.ch/publication/2219.

International Energy Agency. 2015a. *World Energy Outlook 2015: Methodology for Energy Access Analysis*. http://www.worldenergyoutlook.org/media/weowebsite/2015/EnergyAccess_Methodology_2015.pdf.

International Energy Agency. 2015b. Energy Access Database. Database. International Energy Agency. http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/.

IRENA. 2016. *REmap: Roadmap for a Renewable Energy Future*. Abu Dhabi. www.irena.org/remap.

Johnson, K. and E. Hebert. 2012. *Direct current to direct current - A bridge to zero net energy*. *World Renewable Energy Forum*. Vol. 5. http://www.scopus.com/inward/record.url?eid=2-s2.0-84871597180&partnerID=40&md5=86d213b85e9ac1646c327358e336ee11.

Kempener, R. and E. Borden. 2015. *Battery Storage for Renewables : Market Status and Technology Outlook. Irena.*

Kempener, R., O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen. 2015. *Off-Grid Renewable Energy Systems: Status and Methodological Issues*. Abu Dhabi. http://www.irena.org/DocumentDownloads/Publications/IRENA_Off-grid_Renewable_Systems_WP_2015.pdf.

Kolar, J.W. and J. Miniböck. 2012. High-performance rectifier system with 99.2% efficiency. *Power Electronics & Power Supply*(March).

Kroon, B. Van Der, R. Brouwer, and P.J.H. Van Beukering. 2013. The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis. *Renewable and Sustainable Energy Reviews* 20: 504–513. http://dx.doi.org/10.1016/j.rser.2012.11.045.

Laudani, G.A. and P.D. Mitcheson. 2015. *Comparison of cost and efficiency of DC versus AC in office buildings*. London. http://www.topandtail.org.uk/publications/Report_ComparisonofCost.pdf.

Lighting Global. 2016. *Off-grid Solar Market Trends Report 2016*. https://www.gogla.org/wp-content/uploads/2016/03/Off-Grid-Solar-Market-Trends-Report-2016.pdf.

Oliver, S. 2012. *High-voltage DC distribution is key to increased system efficiency and renewable-energy opportunities*. http://www.vicorpower.com/documents/whitepapers/wp-High-voltage-DC-Distribution.pdf.

Park, W.Y. 2011. *TV Energy Consumption Trends and Energy-Efficiency Improvement Options*. *Lawrence Berkeley National Laboratory*. http://escholarship.org/uc/item/8mk3d4k5.

Perez, R. 2006. Off-Grid Inverter Efficiency. *Home Power*(July): 36–37. www.homepower.com.

Price, M. 2016. *Smart Villages Forward Look Workshop Report: Social Enterprises and Industrial Markets for Smart Villages in Developing Countries*. Cambridge, UK.

Salomonsson, D. and A. Sannino. 2007. Low-voltage DC distribution system for commercial power systems with sensitive electronic loads. *IEEE Transactions on Power Delivery* 22(3): 1620–1627.

Salomonsson, D., L. Söder, and A. Sannino. 2009. Protection of low-voltage DC microgrids. *IEEE Transactions on Power Delivery* 24(3): 1045–1053.

Sanjeev, P., N.P. Padhy, and P. Agarwal. 2015. DC grid initiative in India. *9th IFAC Symposium on Control of Power and Energy Systems (CPES)*(February): 1–6.

Savage, P., R.R. Nordhaus, and S.P. Jamieson. 2010. *DC Microgrids: Benefits and Barriers*. Vol. 26.

Savvantidou, S., T. Miyazaki, S. Pourreza, M. Britto, P. Lau, S. Tsubasa, K. Ezawa, et al. 2014. *Energy Darwinism II: Energy Storage: Game*

Changer for Utilities, Tech & Commodities. Citi Bank. www.citi.com/citigps.

Schultz, R., A. Suryani, A. Fadhilah, C. Gruber, and D. Novitasari. 2013. *Productive Use of Energy (PUE): Findings of the EnDev Indonesia Pilot Project*.

Scott, A. 2015. *Building Electricity Supplies in Africa for Growth and Universal Access.* http://2014.newclimateeconomy.report/misc/working-papers/.

Scott, A. and C. Miller. 2016. *Accelerating access to electricity in Africa with off - grid solar: The market for solar household solutions*. London. http://www.odi.org/publications/10200-accelerating-access-electricity-off-grid-solar.

Smart Grid Interoperatibility Panel. 2016. *Local Grid Definitions*. Berkeley, CA.

SOLShare. 2016. *SOLShare: The next generation of DC Nanogrids*. http://microenergy-foundation.com/solshare/wp-content/uploads/2014/12/MESOLshareGIZ_v2DC.pdf.

Tata Technologies. *The story behind the eMO*. http://www.tatatechnologies.co.uk/wp-content/uploads/2013/02/Tata-Tecnologies-eMO-White-Paper.pdf.

Thomas, B.A., I.L. Azevedo, and G. Morgan. 2012. Edison Revisited: Should we use DC circuits for lighting in commercial buildings? *Energy Policy* 45: 399–411.

US Department of Energy. 2014. *Annual Energy Outlook 2014*. Washington, D.C. https://www.eia.gov/todayinenergy/detail.cfm?id=15471.

Vignola, F., F. Mavromatakis, and J. Krumsick. 2008. Performance of PV Inverters. *American Solar Energy Society - SOLAR 2008: Catch the Clean Energy Wave*: 628–650. http://www.proceedings.com/03435.html.

Waide, P. and C.U. Brunner. 2011. *Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems*. Vol. na.

World Energy Council. 2015. Average electricity consumption per electrified household. Database. World Energy Council. https://www.wec-indicators.enerdata.eu/household-electricity-use.html.

Cite as: Kopec, Grant, Price, Michael B., Holmes, John, (2016). The future of direct current electrical systems for the off-grid environment. Report. Smart Villages: New Thinking for Off-Grid Communities Worldwide. Cambridge, UK.

Solar engineering trainer, Barefoot College, India

Tilonia India, Barefoot College -

From September 2011 to the following March, women travelled from across Africa, from countries like Uganda Liberia and South Sudan, to take part in training to become solar engineers.

Each was selected or nominated by her local community and supported by a variety of local and international organisations, and in some cases, their governments. Their trainers, who mostly speak Hindi, must cut across linguistic and cultural barriers using gestures and signs.

Photo Credit: UN Women/Gaganjit Singh

https://flic.kr/p/bVNm1L

SMART VILLAGES

New thinking for off-grid communities worldwide

This publication was made possible through support from the Cambridge Malaysian Education and Development Trust and the Templeton World Charity Foundation. The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the Cambridge Malaysian Education and Development Trust or the Templeton World Charity Foundation.