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Batteries – a key constraint for off-grid solar

Experiences from EU-supported projects 2007-2019

7 AFFORDABLE AND CLEAN ENERGY

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

ACP-EU Energy Facility *Monitoring*

European Commission

DANISH ENERGY MANAGEMENT DEM FOR SUSTAINABLE IMPACT

The ACP-EU Energy Facility (http://energyfacilitymonitoring.eu)

This discussion paper is one in a series of discussion papers based on experiences from the ACP-EU Energy Facility (EF).

The EF was established in 2005 to co-finance projects on increasing access to modern and sustainable energy services for the poor in African, Caribbean and Pacific (ACP) countries, especially in rural and peri-urban areas. 173 project proposals have been granted co-funding from the EU for a total of 0.4 billion euros; 50% of the total project-budgets of 0.8 billion euros.

The projects have been, and are being, implemented in the period 2007-2021 with 90% of projects completed in 2019. The projects cover a wide range of technologies:

Electricity grid-extensions in rural and peri-urban areas, hydro-powered mini-grids, solar and hybrid-solar mini-grids, stand-alone solar solutions for businesses, households and public institutions, portable solar equipment mainly used for lighting, clean energy solutions for cooking such as improved firewood and charcoal cook stoves as well as biogas, biofuels for electricity generation, and capacity development of public institutions in the energy sector.

Among the 173 Energy Facility projects, 71 have promoted off-grid solar where batteries are of key importance.

Danish Energy Management (DEM) has been granted the contract of providing technical assistance for the monitoring of the EF projects in the period 2011-2019. This discussion paper is based on information and data gathered during this period as well as current research and experience from other development interventions.

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Introduction

The world is undergoing a green energy transition and the limitations of today's battery technology is one of the key constraints in a range of different sectors. Affordable, optimal sized battery solutions have become the main constraint for a green energy transition on a global scale and political and economic factors are increasing incentives to invest in developing the technology.

In the energy sector in the developed countries, renewable energy is taking an increasing share of the energy mix. But renewable energy, particularly solar and wind, is more intermittent than its fossil equivalents, and this increases the need for batteries. The function of batteries in this context is to store energy for longer periods of time, for example to save solar energy for night time usage, or to reinforce the grid in the short time when one energy source is taking over from another, or to respond to short peaks in consumption. In transportation, electrical motors are already superior to thermal ones in terms of performance, durability and noise-pollution, but the low energy density in batteries compared to gasoline or diesel is limiting the reach of electrical cars and increasing their cost.

This paper describes the general principles of battery technology, provides an overview of those most frequently used in off-grid electrification in developing countries, and provides examples of projects supported by the ACP-EU Energy Facility that make use of these systems. The potential environmental hazard being created and possible solutions to these are discussed, as well as trends that could be decisive for batteries in the future.

Improvements in battery-technology and innovations in the applications of batteries will contribute to goal **7 – Ensure access to affordable, reliable, sustainable and modern energy for all.** Innovations in component sustainability and better practices for managing used batteries will contribute to goal **12 – Ensure sustainable consumption and production patterns.**

Background

The discovery of the basic principles in an electrical battery is often credited to the Italian scientist, Alessandro Volta, who in 1800 discovered that it was possible to control electro-chemical reactions. Those basic principles have not changed significantly for the majority of battery types: like in 1800, a battery today is composed of an "anode" (-) and "cathode" (+), for instance zinc and silver, that readily engage in 'electron-swapping' through an "electrolyte" which can be an acidic compound.

A rechargeable battery follows the same principles but allows for the current to be reversed making the cathode the anode and vice-versa. The French scientist Gaston Planté developed the first rechargeable battery in 1859 based on lead-acid, with lead in both the cathode and anode and with an acidic fluid electrolyte like the one in Volta's experiment 59 years before.

The choice of which specific chemicals to make up the elements of the battery have changed considerably since Volta and Planté. Especially in the 1960s and '70s, a huge variation of combinations where developed that were optimized in the subsequent decades, to improve on capacity and efficiency.

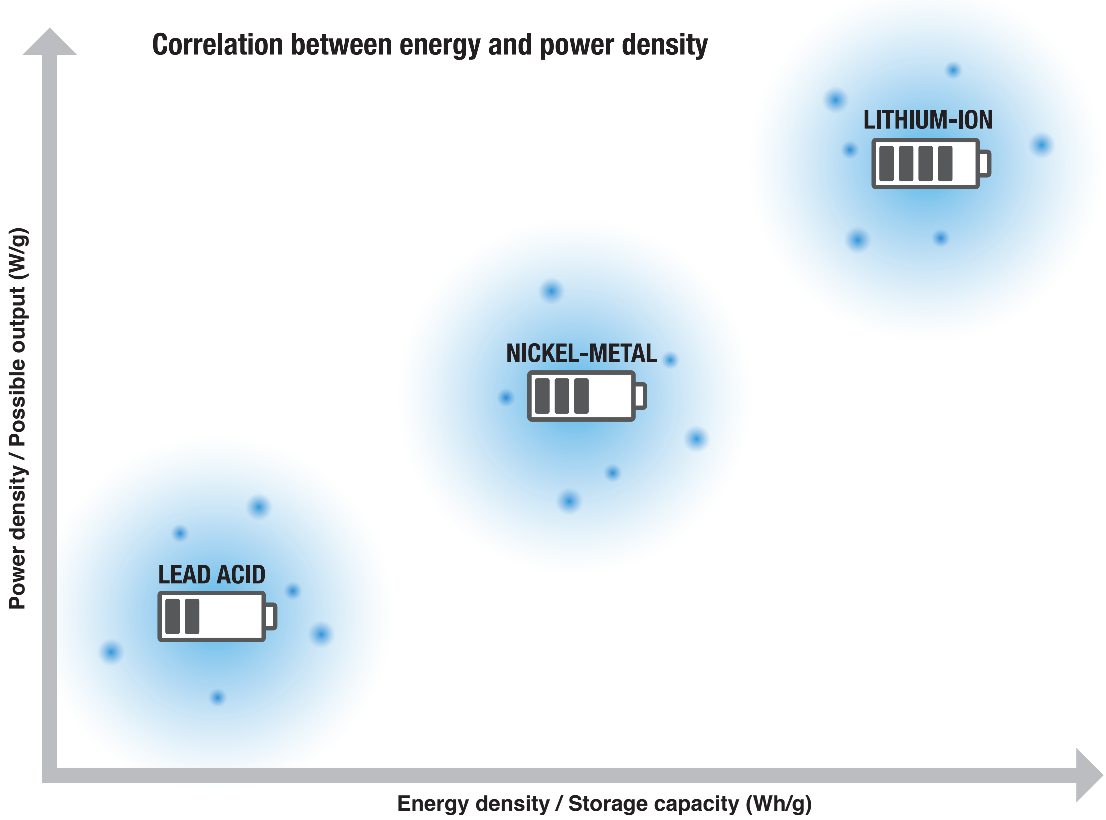
Technology overview

Among the many battery types existing today, there are three that are used mainly in off-grid electrification: 1) lead-acid: either fluid or solid-state electrolytes; 2) lithium-ion: the cathode is made of an alloy of ionized lithium and the electrolyte is solid; and 3) nickel-metal hybrid. However, in recent years, lithium-ion has a significant market share due to safer technology and price decrease.

When choosing the kind of battery that is needed, the physical mass of the battery is a critical factor in terms of maximum power and energy density or storage capacity. The more mass a battery has, the higher power outputs[1] it can produce and the more energy it can store. High outputs are mostly relevant when the battery needs to supply mechanical processes or heating/ cooling services like welding and refrigeration, although the latter is less energy intensive. Lighting and communication services require much less energy.

The different battery types have different properties broadly represented in figure 1.

Figure 1: Power and energy density of different battery types



The combination of chemicals used affect the properties of the battery. For example, different types of lead-acid batteries will vary in terms of performance within the range illustrated above. As shown above, lithium-ion batteries are superior to lead-acid batteries of the same mass. Therefore, even though lead-acid batteries are less expensive, more are needed to provide the same energy-service.

[1] The power output concerns how fast the battery is discharged and, thus, how intense or strong the power it generates. It is most often measured in Watts which is Amperes x Voltage. Storage capacity is most often measured in Ampere hours (Ah) which can be recalculated kWh if the voltage is known. As voltage slightly changes over time, Ah is more precise than Wh.

Duration

One of the most crucial questions concerning batteries is their longevity: How many years can they operate at an optimal level? The lifespan of a battery is not expressed in time but in the terms of life cycles, where one cycle is the process of discharging and recharging the battery. The longevity in years can then be estimated based on assumptions relating to the use of the battery. A solar home system, for instance, probably runs through 350 cycles per year as it performs one cycle per day; if its maximum number of cycles is 2,000, it will then be likely to last approximately 6 years.

The number of cycles that a battery can last depends on many factors of which the following three are the most important:

- Depth of discharge (DoD): The more a battery is discharged before it is recharged, the faster it is worn out. However, the DoD-effect on the cycle life is related to the type of battery. The number of cycles a lead-acid battery can run drops gradually as DoD increases however most lithium-ion batteries have approximately an unchanged number of cycles in them up until 80% DoD at which point the number of cycles drops dramatically.

- Temperature: Batteries do not respond well to high temperatures. For most types, durability drops if they become warmer than 25 degrees Celsius. Again, lead-acid batteries are more sensitive to this factor, than lithium-ion.

- Charging/discharging current: Batteries are designed to be charged at a certain current, the C-rate, which could for instance be 60 Amperes. The fewer amperes the battery is discharged with, the longer it will last and vice-versa.

While the charging and discharging current can be controlled in the design of systems, specifically the Battery Management System (BMS) that can simply cut-off the battery if voltages drops too low or peaks too high, DoD and temperature are harder to control. The graphs below compare the longevity of a lithium-battery with an AGM-battery (a solid-state lead-acid battery)[2]. Three important factors are important to note in order to make a relevant comparison:

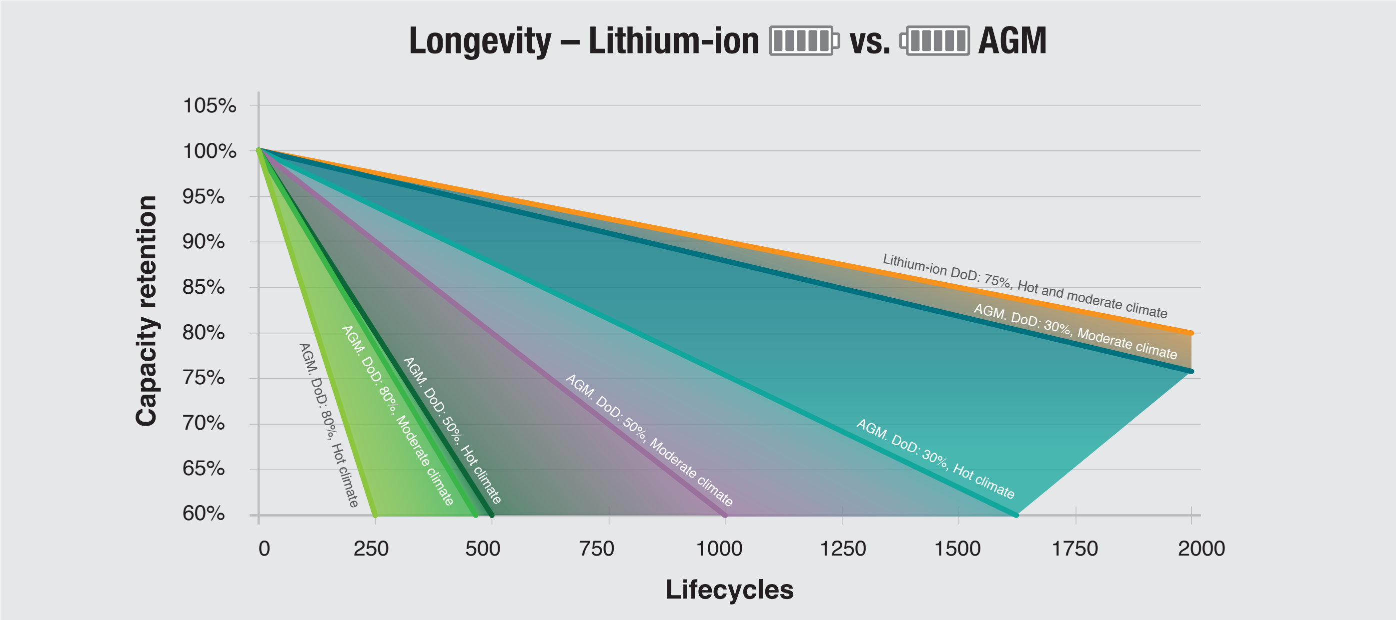
1) A lithium battery performs just about the same until it reaches approximately 75-80% DoD while an AGM battery is much more sensitive to DoD. The lithium battery is therefore compared to the AGM battery in three DoD states, 80%, 50% and 30%.

2) As the voltage of a battery drops along with the decrease in the retention capacity of the battery, the battery will be practically useless around 80% for lithium batteries while AGM batteries can perform perfectly until 60% and between 60-80% if maintained correctly.

3) The lithium battery is much less sensitive to temperature and performs well up to 45 degrees Celsius, while the performance of an AGM battery is affected above 25 degrees Celsius.

[2] Based on a study by Said Al-Hallaj and J.R Selman in Journal of Power Sources, Volume 110, Issue 2, 341-348.

Figure 2: Lifecycles of lithium-ion and AGM batteries in different climates



As shown in figure 2 above, the two best batteries for hot and moderate climates are lithium-based, and the AGM-battery at 30% DoD performs best in moderate climates (below 25 degrees Celsius most of the time) both having the capacity for approximately 2,000 cycles. This means that an AGM battery is a relevant substitute for a lithium battery and could even last longer if well maintained. However, AGM batteries needs to have 2-2.5 times the storage capacity and only if temperatures are kept moderate.

From Figure 2, it is apparent how sensitive the AGM battery is to atmospheric temperature and DoD which are also correlated: The higher the DoD, the more sensitive the battery is to increased temperatures. To illustrate this, an AGM battery with 80% DoD in hot climate (below 45 degrees Celsius) can only withstand 250 cycles with proper maintenance, which is 8 times less than a lithium battery used under the same conditions.

Relative benefits of lithium-ion for off-grid electrification

There are five aspects in which lithium-ion batteries out-perform lead acid batteries and that are relevant for off-grid electrification:

1) the weight of the battery for comparable power and capacity;
2) the DoD threshold before the number of life cycles is affected;
3) linked to this, the sensitivity to periods of redundancy;
4) the sensitivity to high temperatures;
5) the solid state, which implies less maintenance.

The factors are important to consider due to the context in which off-grid electricity is often implemented.

Experiences from the ACP-EU Energy Facility

71 projects in the ACP-EU Energy Facility (EF) has promoted off-grid solar which always include batteries for the simplest of reasons: The PV panels generate electricity during the day, while people's first need for electricity is lights in the evening and the night. That means that batteries are always part of off-grid equipment no matter how small it is: Solar lanterns, Solar energy service centres, Solar Home Systems (SHS) and solar mini-grids.

Table 1 Overview of off-grid solar projects in the ACP-EU Energy Facility[3]

	Solar lanterns	Energy Service centers	Solar Home Systems	Solar and solar-hybrid mini-grid
# of EF projects	21	5	40	26

In the following, we will go through a few and highlight experiences from the EF.

Solar lanterns

Solar lanterns are good substitutes for battery torches and kerosene lamps. The lantern is technically similar to a battery torch, the only exception being that it comes with a rechargeable battery that is designed to be charged by a PV panel. Solar lanterns are almost always designed with an LED bulb. The use of LED is advantageous for off-grid solar as PV panels generate DC current and LED also uses DC current; the combination PV-LED does away with the need to invert electricity to AC and less electricity is lost in components.

In the EF, two models for charging of solar lanterns are generally used: the lantern either has an integrated PV-panel or the lanterns are recharged at a 'solar charging station' for a fee. The charging station is equipped with PV panels that charge a larger battery which in turn recharges the lanterns.

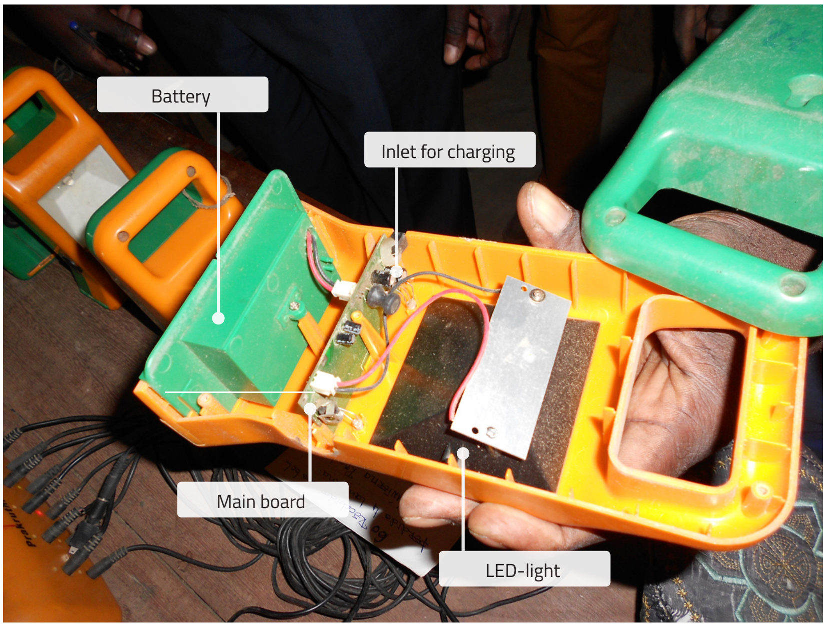


Photo: Danish Energy Management (DEM)

[3] Several of the 79 projects have promoted different off-grid solar solutions and are counted in several cells.

Photo: DEM

The above photos are from the EF-project *Enabling 18.000 people to access sustainable small-scale solar power in 2 districts of Cabo Delgado* in Mozambique. The yellow lanterns are charged by battery chargers (green box). The batteries applied in the green box is lead-acid that after 5 years were not working anymore in most of them, meaning that they could not discharge at sufficient voltage to charge the lanterns. The photo above shows how the charging station operator keeps his business going by boosting the current coming out of the battery (the white box on the table) with a car battery (the black box) has found a solution to increase the services offered in his small business, by taking out the battery of the battery charger (the white pack), boosting it with a car battery (the red-black pack) and charging it with PV panels (the wires exiting the picture to the right). The battery is then connected to the battery charger through the front and the lanterns can then be recharged with the correct current.

The above project only provided charging of solar lanterns, but several other EF projects in this category combined the service with leasing of battery boxes *(Solar energy for rural Kenya)* or developed the concept into a kiosk selling all types of small retail *(POWER KIOSK: Scaling-Up Rural Electrification in Kenya, Ethiopia and Madagascar).*

Energy service centres

Energy service centres have arisen out of a need for additional services besides charging solar lanterns, such as cell phone charging, solar lantern charging, TV, cooling etc. The energy service centre offers all these services and based on the results of the project supported by the ACP-EU Energy Facility, demand is high for refrigeration, entertainment (TV), cell phone charging and mechanical services, such as grinding flour and welding. Energy service centres can also host barber shops, mobile money agents, sewing, air compressor for pumping tyres, restaurants, etc.

The energy service centre can have many names. Several has been promoted in Mauritania under the name "Plateforme solaire" as a PV version of the popular "Multi-functional Platform" promoted in especially West Africa by UNDP. in the equipped with many PV panels and larger battery-packs to allow for more energy intensive uses. As described above, the greater output needed for refrigeration and welding necessitates larger battery configurations (e.g. connecting a greater number of batteries in series).

A solar energy service centre in Mauritania; EF-project ERUDI. Photos: DEM

The solar platform promoted in *Électrification rurale décentralisée interrégionale en Mauritanie (ERUDI)* added an especially challenging service; welding. Welding uses short peaks of high watts which is a difficult task for most batteries. As explained previously, the specific power that the batteries can provide depend on their size and chemicals used and their duration depend on how soft they are discharged. So, welding requires a somewhat different solution than other services, like refrigeration and mobile phone charging. ERUDI solved the problem by integrating to parallel circuits: One circuit with a set of batteries for most services, and one circuit with a set of batteries dedicated to welding.

Solar Home Systems

Solar Home Systems (SHS) are the technology that forms the basis of many growing companies in East Africa using mobile money services to collect payment or to manage payment defaults. SHSs have smaller batteries and therefore a lower output. A range of SHS exists of different sizes depending on the energy services they offer. Recently, the growing use of lithium-ion batteries and the availability of DC appliances (TVs, fans, refrigerators, freezers, and light bulbs) means that the scope of services that can be provided with a SHS is rapidly increasing. The investment cost is kept to a minimum due to the scalability of the system and the user is able to manage the system and perform basic maintenance.

The majority of the SHSs sold in Africa today are believed to be in the range from 20 to 100 W. The cheapest 20 W system costs around €200, while for a 100 W system the total cost ranged from € 660 to € 1,156 (IRENA, 2016). The system specifications of SHSs can vary widely, with inexpensive entry-level systems offering smaller battery storage capacity to reduce costs and increase affordability.

Battery costs account for the largest single share of the SHSs, with a simple average of 29 % of the total costs (€2.45/W). The PV modules themselves, as well as the lighting fixtures and wiring, are on average around 20 % (€2/W) of the total installed costs, soft costs account for 22 % (€1.82/W), other hardware for 21 % (€1.82W) and the charge controller for 7 % (€0.64/W) (IRENA, 2016). This means that a battery failure, which is one of the most common defects that occur with SHSs, can have a significant replacement cost for households (Quak, 2018).

A local company in Burkina Faso has designed their own box for the lead-acid batteries, that can be locked to avoid misuse. Photo: DEM

The SHS for a household in this picture provides for phone charging (on the wall), lighting, satellite TV and a fan. Photo: DEM

It makes a big difference how sizeable the batteries are which, in turn, depend on the use. The phots above are from the project *Microcrédit solaire et changement d'échelle au Burkina Faso, MICRESOL.* The local company in charge of the technical setup opted for a dual system: DC installation for lights and DC appliances like an LED television can be; AC installation for open plugs and appliances where only alternating current products were locally available. Freezers, that were popular in restaurants for instance, used DC.

Mobisol's SHSs come with a range of different DC-appliances for home and small business use: lights, TV, satellite-decoder, hair clippers, stereo and loudspeakers, as well as cell phone charging ports. Several SHS companies besides Mobisol offer a range of appliances based on the same principles. Photo: DEM

The development of DC-appliances and batteries let the project *Prepaid Energy – Rent to own solar home systems (off-grid)* in Rwanda to change their product range dramatically. From their start in 2014, a SHS equipped with a 100-watt panel, controller, inverter and lead-acid battery could service the client who could plug in any equipment they wanted but by 2018, 20 watt and 40-watt versions were added to the project.

The smaller systems used Lithium-ion batteries who were much smaller due to the ability to reach 80% depth of discharge with this type without reducing the lifespan of the battery and because these smaller systems came with the most frequently used appliances: lights, fan, tv that ran on DC and discharged the batteries at the optimal rate. Through this innovation, the end user experienced a similar energy service with 40 watts than he had done with 100 watts, but at a lower cost to him and the company simply by optimising on the battery technology and how it was discharged.

Solar PV mini-grids

While energy service centres can provide many services, they rarely provide electricity in people's homes. Solar PV mini-grids distribute electricity to customers within the area, giving them an energy service that can be comparable to a grid connection, depending on the capacity of the system installed. The quality of supply depends mainly on the storage capacity and specific power of the batteries: batteries that are inappropriately sized means a high risk of outage and weakened service when used for mechanical purposes or welding. Many PV mini-grids are equipped with back-up diesel-generators (solar-hybrid mini-grids) to provide a more stable service for instance in cloudy weather.

A large bank of batteries is needed to supply a mini-grid. Batteries need to be stored in a ventilated room. In this mini-grid, liquid-state lead-acid batteries were chosen. Photo: DEM

The power house for a PV mini-grid in Ivory Coast. Photo: DEM

The electricity is distributed throughout the village. Photo: DEM

The type of batteries often found in the EF mini-grids are liquid-state OPzS batteries (wet lead acid batteries). OPzS batteries are good value for money (low $/[full lifetime kWh]) but requires regular refilling of deionized water, thus, refilling with rain water and not water from a borehole.

The above photos are from the EF-project *Electrification des communautés rurales avec des Micro-réseaux de Génération d'Energie Solaire Photovoltaïque Autogerés dans la Région de Zanzan (Côte d'Ivoire)* that applied this very solution and trained a local maintenance team in the correct procedures. The EF-project Light up our Futures in Liberia uses the same approach.

PV mini-grids are often promoted because they are said to be able to support productive uses: Milling, grinding, saw mills, welding etc. However, these types of energy use require high loads to perform, which is a challenge for PV mini-grids. The EF-project, Light Up Liberia, installed a mini-grid in a rural area of Liberia but to the dismay of the small businesses there, the project rejected high-load services because it grid was not dimensioned for it and the main constraint here is the batteries.

The EF-project, *Programme d'électrification solaire en milieu rural dans la Province du Zoundwéogo*, specifically targeted small business and installed lithium-ion batteries capable of providing high loads as well as configuring the components with two inverters: One between the batteries and the grid, and one that could either lead the DC current directly to the battery parc or invert it to AC for the grid. This meant that many productive uses could be serviced during the daytime with limited load shedding in the system. However, the project had under-dimensioned the number of PV-panels, and little electricity was left to provide the basic service of lighting in the night-time. This problem is hopefully solved in the future by adding additional PV panels.

Solutions to key obstacles of batteries

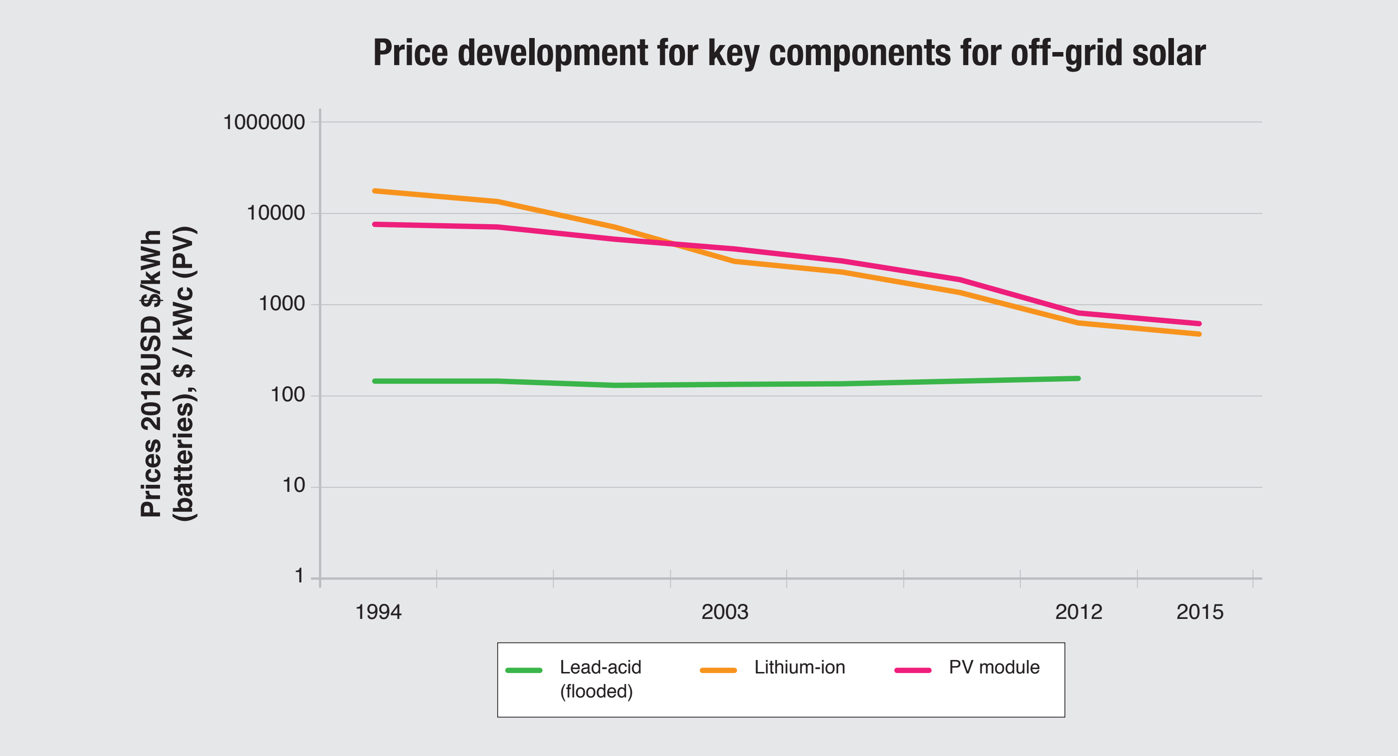
The key obstacles identified across EU-supported initiatives in the Energy Facility relate to the high cost of batteries, the deep discharge that reduces longevity considerably, and the sheer space needed to accommodate batteries.

High proportional cost

While the cost of PV panels and auxiliary equipment (inverters and charge controllers) have dropped remarkably in the last decade, the proportion of the cost of batteries of the overall investment has actually increased slightly in recent years. This is because the price of Lithium-ion has dropped rapidly but is only now beginning to reach comparable price levels to lead-acid batteries, as shown in figure 3 below.

The only possible way to mitigate this and enjoy the full effect of the price-drop of the PV panels while still maintaining the level of service, is to increase energy efficiency by using more efficient appliances or conserve energy by limiting the service to periods of greatest demand.

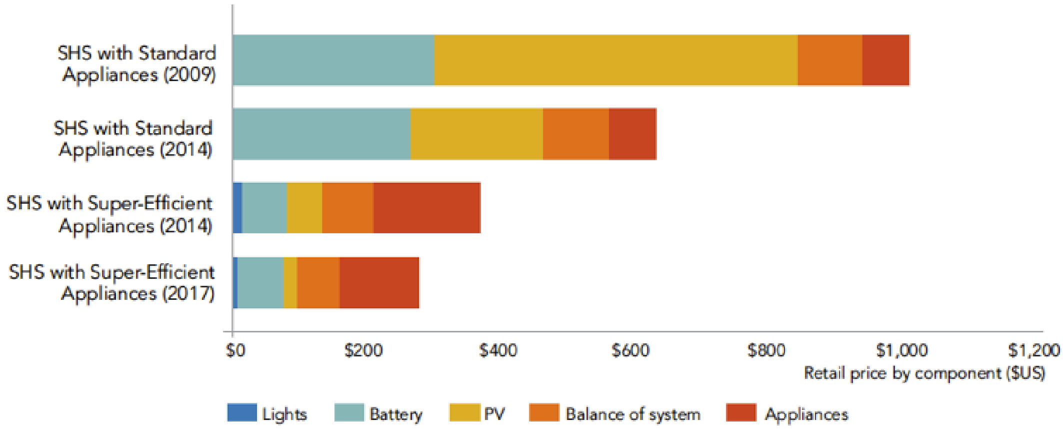
Figure 3 Price development for Lithium-ion and lead-acid batteries, and PV modules [4]



According to a recent analysis "the upfront cost of a typical off-grid energy system can be reduced by as much as 50 percent if super-efficient appliances and right-sized solar PV and batteries are used, while delivering equivalent or greater energy service" (Van Buskirk, 2015). Thus, advances in energy-efficient devices now allow households to reap more benefits from the relatively small amounts of electricity available to them. Instead of illuminating a single light bulb, CFLs and LED lamps use provide more and better light and consumer less energy, leaving enough energy to power other electronic devices such as fans and low-wattage TVs and appliances (WB, 2017).

[4] Based on Bloomberg New Energy Finance and Schuyler Matteson & Eric Williams in Energy Policy, Volume 85, October 2015, 71-79

Figure 4 Retail purchase price for SHSs that provide identical levels of service. World Bank 2017



Deep discharge is damaging for a battery

Battery management is crucial if a battery is to last several years. One way to mitigate the risk of mismanagement, is to use lithium-ion batteries that generally can endure many cycles with a high DoD. But even lithium batteries have limits and there need to be safeguards in place to prevent a DoD above 80%.

For lanterns and SHSs, the solution lies in the battery management system (BMS) that must be configured to prevent the system discharging to a level that affects battery performance. This issue can also arise for batteries that are kept in storage, where the batteries slowly discharge. Here, the service provider must monitor the batteries and recharge regularly, especially in the case of lead-acid batteries.

Mobisol Rwanda monitors the batteries in their warehouse to make sure that the client is provided with a battery in good condition. Mobisol, like many other SHS-companies, offer a lease-to-own or pay-as-you-go model, where the company bears the cost of maintenance and repairs, which makes it feasible to invest in preventive maintenance as well.

In the village of Butare, a village that received SHS in the IREA-RPP project, batteries from cellphones are used to keep the PV systems functioning as the batteires that came with the systems does not work properly.

The EF-project *Increase Rural Energy Access in Rwanda through Public Private Partnership (IREA RPPP)* provides an excellent example of this. During the project, SHS was distributed in 10 villages as a demonstration of the technology. For an unknown reason, half of the systems were distributed in 2013 while the other half was distributed in 2015. A post project mission in 2018 found, that many of the systems distributed in 2013 were still functioning while all of the exactly similar systems distributed in 2015 only had worked for a few days. The reason is likely to have been lack of battery maintenance, and the SHS installed in 2015 had reached a DoD where they could not be recharged by the PV panel making the systems useless unless the battery was replaced.

Sufficient capacity requires space

The greater the generation capacity of the system, the bigger the bank of batteries needs to be, and for portable devices, there is a limit to how large the battery can be. This constraint is the main reason for the high uptake of lithium-ion batteries that has the highest energy-density of the battery type currently applied.

Figure 5: Comparison of a PV mini-grid central with lithium and lead-acid battery

	Flooded lead-acid	Lithium alternative (lithium-ion)
Battery capacity and voltage	~3,000 Ah (20 H), 2 V (2.27)	700 Ah (5H), 3 V (3.25)
Configuration	72 batteries in 24S3P	128 batteries in 16S8P
Physical size	72 x 20x50x75 cm (7 m^2 I 5 m^3)	128 x 6x60x30 cm (5 m^2 I 1.5 m^3)
Battery park capacity and voltage	~9,000 Ah, 48 V	5,600 Ah, 48 V
Estimated Depth of Discharge	50%	80%
Estimated lifecycles hot climate	1,400	2,000
Estimated approximate costs	50,000 €	80,000 €
Estimated approximate costs per lifecycle	35 €	40 €

Figure 5 shows how the same battery capacity could Have been provided in one the EF projects[5] using flooded acid-lead batteries. The nominal capacity of PV panels is 31.5 kWc, and the nominal voltage input for the inverter: 48 V. The Lithium-iron alternative is calculated by the author based on data sheets of lithium-iron batteries 2018 prices. Price estimates are based on the graphs of the previous page where 31.5 kWc of panels has a cost of approximately 15.000 €.

All though the lithium alternative is costlier in upfront costs, they require much less space as the batteries are smaller and less ampere-hours are needed as the Lithium-ion can discharge 80% and still last longer. The resulting cost per lifecycle is roughly the same.

Environmental impacts

One of the most overlooked hazards of off-grid electrification is the environmental effect that used batteries pose. The leaching of battery chemicals can cause water pollution, can travel by air through dust or can be absorbed through the skin. In particular, lead-acid batteries have a long list of potential health hazards and pregnant women and young children are the most vulnerable to their effects. The toxicity is dependent on the specific chemical compositions adopted. Also, lithium-ion batteries can in rare cases be explosive (thermal runaways) and leaks should be prevented.

Batteries carved open for their metals and discarded in the street afterwards.

The first obstacle to handling the environmental problem is that few developing countries are enforcing regulation that in practice requires either companies or users to dispose of their used batteries in a responsible way[6] [7].

The environmental code adopted in Burkina Faso, for instance, describes that dangerous waste must be separated from other waste and that waste can only be recycled by companies authorised to do so[8]. But the specific texts concerning control and sanctions have not yet been developed and enforcement is challenging due to a lack of infrastructure[9]. However, several stakeholders in off-grid electrification in developing countries attempt to face the challenge through voluntary arrangements.

Storing used batteries

The simplest arrangement is to safeguard the batteries and keep them out of harms way until a more permanent solution is found. For lack of a better alternative, this approach reduces risk. This approach is applied in the project *Enabling 18.000 people to access sustainable small scale solar power in 2 districts of Cabo Delgado* where charging station operators were instructed to put used batteries in a plastic bag and bury them in the ground.

[5] Electrification des communautés rurales avec des Micro-réseaux de Génération d'Energie Solaire Photovoltaïque Autogerés dans la Région de Zanzan (Côte d'Ivoire)

[6] In Sub-Saharan Africa, South Africa is the exception to the general rule that while disposing batteries might not be legal no public or publicly regulated collection of batteries takes place.

[7] Williams, Mari & Retamal, Monique & Dominish, Elsa & Green, Joanne & Schroeder, Patrick & Gower, Richard & Kendal, Julia. (2018). Bending the Curve: Best practice interventions for the circular economy in developing countries.

[8] Loi n°006-2013. Portant code de l'environnement au Burkina Faso

[9] Ministère de l'environnement, de l'Economie verte et du Changement Climatique (MEEVCC) présentation à Dakar, Décembre 2016.

Paying for used batteries

Stakeholders that distribute batteries, like SHS companies, can also provide incentives to their clients by offering a rebate for the return of a used battery, perhaps in the form of a discount on the replacement; the SHS-company can then resell those batteries in large bulks for recycling in factories. As batteries often contain valuable metals, small battery collectors buy used batteries, empty the electrolyte, remove the metals and discard the casings (causing another pollution hazard) form part of the informal economy in many countries[10].

A SHS company could be competing with such vendors to obtain batteries if their price is too high, on the other hand, the market value of battery-chemicals is low, which means that they can't pay a lot either. The few companies that engage in this, are not doing it for the business case, but due to contractual conditions stipulated by financing partners, or as part of a Corporate Social Responsibility (CSR) policy.

The project *Microcrédit solaire et changement d'échelle au Burkina Faso, MICRESOL* has adopted a strategy of buying used batteries in SHS-systems from the customers and reselling them to battery-collectors who have received official authorisation from the Ministry of Envrionnement to collect this type of solid waste[11]. As batteries are not recycled in Burkina Faso, the batteries are most likely being transported to Accra in Ghana to be shipped out for recycling in France or China.

Selling used batteries for recycling

When batteries die out, it is often because the electrolyte ceases to be able to transport electrons between the anode and cathode efficiently. So, the components could be reused in a new battery. Few countries recycle batteries, as large quantities are needed to make it feasible. The battery manufacturers in India and China, as well as a range of European countries, buy batteries from third world countries. However, as the price of a battery is low to begin with, the profit margin is extremely low when batteries need to be shipped over longer distances. In the EF project *Électrification rurale décentralisée interrégionale en Mauritanie (ERUDI)* an analysis was made as to how batteries could be recycled locally (in a responsible way) but the vast amount of batteries needed to make recycling profitable was a detriment to this idea by the time of the project.

Currently, the number of recycling plants has, however, increased dramatically in Kenya and more seem to be in the pipeline in Eastern Africa[12]. This may promote recycling as the infrastructure develops. The EF project, *Prepaid Energy – Rent to own solar home systems (off-grid)*, signed a partnership agreement with a recycling plant in Kenya for their project in Rwanda and started to collect batteries.

But in order to ensure that the volume of batteries is adequate to run a feasible recycling plant, government regulations are needed to obligate responsible disposal through authorised channels, public or private, for a long-term solution.

The future of batteries

As explained in the introduction, battery technology is evolving. The sheer increase in the production of batteries worldwide is fuelling investment in new battery factories, which is increasing competition and therefore pushing the price down. As the battery is one of the main constraints in all portable electric appliances and machines from laptops to electric vehicles, intensive research is going into optimising existing chemical compounds and experimenting with new ones.

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[10] https://www.ila-lead.org/.../Recycling in the Informal Sector

[11] Following article 53 in the Environmental Code from 2013.

[12] See http://www.abmeastafrica.com/recycling for an example

Lithium-ion

There exist many chemical variants of lithium-ion. The emergence of Tesla in the automotive marketplace has stirred a great deal of research interest in the specific lithium-cobalt-iron battery used in Teslas and varieties of this, but other lithium-based models are also being researched[13].

Flow-batteries

One of the types of batteries undergoing extensive development these years is the redox-flow-batteries or just flow-batteries. Although the principles underlying this battery have been established for decades, recent breakthroughs in design and chemical combinations have made flow-batteries an emerging, innovative technology.

In a redox-flow-battery, the energy is stored in the electrolyte which, among other interesting features, creates the possibility of altering the power density and storage capacity for the specific use. The two are not necessarily linked in flow-batteries. Also, organic variations of the battery component exist that are composed of very inexpensive materials but are still toxic. The extremely toxic compound, Vanadium, has caught the interest of researchers as vanadium can react with vanadium itself at different oxidation states, doing away with the need for different chemistries in the anode and the cathode.

The types of chemistries applied in flow-batteries often have very low energy densities and are physically designed in large container tanks. They are currently applied for grid-reinforcement, optimising on their quick response time to drops in voltage, but only in developing countries and only on an experimental level, so far.

Metal-air-batteries

At the other end of the scale, metal-air batteries are being developed especially for their high energy density. Like any other battery, metal-air batteries use oxidation-reduction reactions, with pure metal as the anode and 'ambient' air as the cathode. What is needed is an electrolyte that allows for an efficient and controlled reaction process and this is what is currently primarily holding metal-air batteries back from exploiting their theoretical potential. Also, it is the oxygen in 'ambient' air that is causing the reaction, so the higher O2-content, and thus, the less 'ambient' the air is, the more efficient it will be. It is still too early to tell if metal-air batteries will overcome these barriers.

Advances in environmental protection

While it is evident that management of electrical waste and recycling of batteries is not as advanced in developing countries, battery recycling techniques have not yet caught up with the rapid uptake of rechargeable batteries in developed countries. The most widely applied recycling processes consists of breaking down the components and reusing these for new batteries. But, actually, worn out rechargeable batteries often just suffer from sedimentation-alloying in the electrode and the cathode and anode could most likely be reused without breaking it down.

Exactly how this 2nd generation recycling process can function will of course depend on the specific chemistries involved and the most common usage, as well as the reason for the malfunction. This is a new area of research and still too early to tell if this can be applied feasibly on a larger scale, which in turn will also depend on political incentives.

[13] For a still relevant overview of the scientific roads pursued see "Recent advances in rechargeable battery materials: a chemist's perspective", M. Rosa Palacín. Chemical Society Reviews, March 2009.

One thing seems evident, in a decade or two, batteries are most likely going to be very different from what we know today and as batteries are currently the critical constraint for rural, off-grid electrification, that could change the sector fundamentally in terms of effectiveness, cost and environmental impact.

Recommendations

- Analyse the pros and cons of different battery types before choosing the type to apply for off-grid rural electrification in the ACP-region. Be especially aware of the advantages of lithium-ion types.

- Apply DC appliances in combination with off-grid solar whenever possible as it improves the performance of the overall system.

- The market for SHS is driving the development in a direction where lithium-ion and integrated DC appliances are becoming the off-the-shelf solutions. Be aware that this is an advantage for energy efficiency but also takes away choice for the end user, who is bound to use the appliances sold to him by the same company that provides the SHS.

- Ensure that acid-lead batteries are not left to discharge when stored and verify the battery capacity at the time of installation (which could be very different than the capacity they had when they were procured)

- Integrate handling of end of life batteries when promoting off-grid solar. If possible, integrate battery-collection in the business plan or continuation strategy.

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Other useful links

http://batteryuniversity.com

https://www.batterysolutions.com/recycling-information/

http://www.irena.org/publications/2015/Jan/Battery-Storage-for-Renewables-Market-Status-and-Technology-Outlook

http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

https://www.letsgosolar.com

https://pubs.acs.org/page/vi/2015/batteries.html

https://www.ruralelec.org/publications

Annex: List of off-grid solar projects in the ACP-EU Energy Facility

Project #	Project Title	Country	Solar lanterns	Energy Service centers	Solar Home Systems and other Stand-alone PV systems	Solar and hybrid mini-grid
2007/ 195-954	Community Managed Renewable Energy Program For Rural Ethiopia	Ethiopia	✓		✓	
2007/ 195-961	Servicio Energetico Sostenibile para poblaciones Rurales Aisladas mediante Micro-redes con energia renovables en la Isla de Santa Antao (Cabo Verde)	Cape Verde				✓
2007/ 195-964	Best Ray (Bringing Energy Services to Tanzanian Rural Areas)	Tanzania	✓		✓	
2007/ 195-974	Somalia Energy and Livelihood Project (SELP)	Somalia			✓	
2007/ 195-976	Improved access to Energy services in isolated rural areas of Mozambique by application of photovoltaic systems	Mozambique			✓	
2007/ 195-978	Red de centros de servicios energéticos básicos alimentados con sistemas fotovoltaicos basados en la mejora de servicios sociales básicos y en desarrollo de capacidades locales y la autogestión	Mozambique			✓	
2007/ 195-984	Providing access to modern energy for northern Uganda (PAMENU)	Uganda			✓	
2007/ 195-993	Developing energy enterprises project East Africa	Kenya; Tanzania; Uganda	✓		✓	
2007/ 195-996	Solar energy for improved livelihood in Burkina Faso	Burkina Faso			✓	
2007/ 196-000	Projet de développement de l'accès des populations rurales sénégalaises aux services électriques (Prodapes – Kolda – Vélingara)	Senegal				✓
2007/ 196-001	Projet d'Initiatives Locales d'Electrification Solaire (PILES)	Mauritania			✓	

Project #	Project Title	Country	Solar lanterns	Energy Service centers	Solar Home Systems and other Stand-alone PV systems	Solar and hybrid mini-grid
2007/ 196-002	Msamala Sustainable Energy Project	Malawi			✓	
2007/ 196-003	Projet d'électrification Rurale dans le Brakna - PERUB	Mauritania	✓	✓		
2007/ 196-007	Projet d'Accès universel à l'électricité : Réseaux et Services publics d'électrification dans 20 localités rurales de 5 wilayas (Régions) en Mauritanie : PELEC 20	Mauritania	✓		✓	
2007/ 196-014	Electrification rurale décentralisée par énergies renouvelables dans le sud de Madagascar (RESOUTH)	Madagascar				✓
2008/ 195-967	Promoting use of sustainable energy in Wajir District	Kenya			✓	
2008/ 195-971	Increased Access to Electricity Services	Zambia			✓	
2008/ 19767	Increase Rural Energy Access in Rwanda through Public Private Partnership (IREA RPPP)	Rwanda			✓	
2011/ 231-578	Community Based Green Energy Project	Kenya			✓	
2011/ 231-611	Mise en œuvre d'infrastructures de production électrique solaires pour des localités rurales isolées de Mauritanie et mise en place de gestionnaires locaux (IPES RURAL)	Mauritania			✓	✓
2011/ 231-781	Providing Solar Home Systems (SHS) to the rural and peri-urban population of the region of Gabú in east Guinea-Bissau on a fee-for-service basis	Guinea-Bissau			✓	
2011/ 231-830	Programa Comunitário para Acesso a Energias Renováveis	Guinea-Bissau				✓
2011/ 232-092	Enabling 18.000 people to access sustainable small scale solar power in 2 districts of Cabo Delgado	Mozambique	✓			
2011/ 232-176	Mejorar el acceso a Fuentes de energía y la organización comunitaria de 7 comunidades rurales pobres de la región fronteriza de República Dominicana y Haití.	Dominican Republic; Haiti			✓	

Project #	Project Title	Country	Solar lanterns	Energy Service centers	Solar Home Systems and other Stand-alone PV systems	Solar and hybrid mini-grid
2011/ 232-318	Rural Sustainable Energy Development in Zimbabwe	Zimbabwe	✓		✓	
2011/ 232-367	Dotacion de Energia Renovable a Comunidades Rurales de Moca	Dominican Republic			✓	
2011/ 232-479	Solar energy for rural Kenya	Kenya	✓			
2011/ 232-617	Électrification rurale décentralisée interrégionale en Mauritanie (ERUDI)	Mauritania		✓		
2011/ 261-902	Electrification intégrale de dix villages du Yatenga (Burkina Faso) axée sur la promotion d'une écozone	Burkina Faso			✓	
2011/ 263-711	Rural Energy Activating Livelihoods	Sierra Leone			✓	
2011/ 264-343	Microcrédit solaire et changement d'échelle au Burkina Faso, MICRESOL	Burkina Faso			✓	
2011/ 264-345	Production durable d'électricité aux services des populations rurales et périurbaines en Afrique: développement du concept « flexy-energy »	Burkina Faso; Mali				✓
2011/ 264-697	Energy for All (E4A) – Alternative Energy Solutions for Rural and Peri-urban Timor-Leste	Timor-Leste	✓			
2011/ 266-256	Increasing access to modern, affordable and sustainable electricity services for the remote islands of Yap, FSM	Micronesia, Federated States of			✓	
2011/ 266-546	Community empowerment for efficient production use and access of renewable and sustainable energy in rural areas in Malawi	Malawi	✓		✓	
2011/ 267-136	TRIODOS – Expanding Sustainable Energy Markets through Microfinance – Energy Enterprise partnerships	Kenya; Tanzania; Uganda	✓		✓	
2011/ 267-189	Projet d'accès aux services électriques des localités de petites tailles de la Région de Sédhiou (PASES) – Sénégal	Senegal	✓		✓	✓

Project #	Project Title	Country	Solar lanterns	Energy Service centers	Solar Home Systems and other Stand-alone PV systems	Solar and hybrid mini-grid
2011/ 267-810	Support the Ministry of Health and Social Welfare of Liberia in providing Renewable Energy Sources to Rural Primary Health Care Facilities	Liberia			✓	
2011/ 267-844	Developing and Demonstrating a Rural Energy Strategy and Master Plan for Liberia	Liberia	✓			
2011/ 268-336	Integrated Approach to Meet Rural Household Energy Needs of Ethiopia	Ethiopia	✓		✓	
2011/ 268-372	Support to Efficient Utilization of Alternative Energy Sources to Improve the Livelihood of Pastoral and Agro pastoral Communities in Southern Ethiopia	Ethiopia			✓	
2011/ 270-457	Facilidad Sur Solar	Dominican Republic			✓	
2011/ 270-635	ProgettoMondo Mlal : – Déployer de nouvelles opportunités de développement socio-économique par l'accès aux énergies durables dans le Plateau Central	Haiti	✓		✓	
2011/ 273-991	Programme d'accès aux services énergétiques, Commune rurale SAFO (PASE)	Niger	✓			
2011/ 280-322	Best Options for Rural Energy and Access to Light and Electricity (BOREALE)	Madagascar				✓
2012/ 023-215	Improving reliable access to modern energy services through solar PV systems for rural areas (outer islands) of Tuvalu	Tuvalu				✓
2012/ 279-396	Programme d'électrification solaire en milieu rural dans la Province du Zoundwéogo	Burkina Faso				✓
2012/ 283-253	Electrification des communautés rurales avec des Micro-réseaux de Génération d'Energie Solaire Photovoltaïque Autogerés dans la Région de Zanzan (Côte d'Ivoire)	Cote d'Ivoire				✓
2014/ 340-491	Promoting Renewable Energy Services for Social Development in Sierra Leone (PRESSD-SL)	Sierra Leone	✓			✓

Project #	Project Title	Country	Solar lanterns	Energy Service centers	Solar Home Systems and other Stand-alone PV systems	Solar and hybrid mini-grid
2014/ 340-503	Eco-Electrification Dynamique dans le nord et le centre-nord du Burkina Faso	Burkina Faso				✓
2014/ 341-047	Micro Power Economy, Tanzania Roll out	Tanzania				✓
2014/ 341-877	Prepaid Energy – Rent to own solar home systems (off-grid)	Rwanda			✓	
2014/ 343-742	Développement durable par les énergies renouvelables (DPER-Sud Est Sénégal)	Senegal				✓
2014/ 344-342	Solar PV Mini Grids for Two Rural Towns of Areza and Maidma and Surrounding Villages in Eritrea	Eritrea				✓
2014/ 344-366	Access to energy services in rural and peri-urban areas in Northern Uganda (Teko Wa Project)	Uganda	✓		✓	
2014/ 344-403	Développement de l'accès à un service électrique durable pour 50.000 personnes vivant dans des villages pôles de développement de MATAM – KANEL – RANEROU - GOUDIRY – BAKEL, très éloignés des lignes électriques	Senegal				✓
2014/ 348-266	Scaling up access to modern electricity services on a regional scale in rural Sub-Saharan Africa by means of a fee for service business model	Cameroon; Guinea-Bissau; Mali; Uganda			✓	✓
2014/ 348-754	Scaling-up rural electrification using innovative solar photovoltaic distribution models	Uganda			✓	✓
2014/ 348-755	Sustainable Energy for Rural Communities (SE4RC)	Malawi; Zimbabwe				✓
2014/ 351-389	Electrification Rurale Décentralisée des Provinces du Ziro et du Gourma (ERD ZIGO)	Burkina Faso				✓
2014/ 351-553	PROGRES-Lait : Programme Régional d'Extension de l'Horizon des Opportunités de Valorisation de la Chaîne de valeur Lait par l'Accès aux Services Energétiques durables	Mauritania; Senegal		✓		

Project #	Project Title	Country	Solar lanterns	Energy Service centers	Solar Home Systems and other Stand-alone PV systems	Solar and hybrid mini-grid
2014/ 352-384	Augmenter et consolider l'accès aux services d'électricité modernes dans le régions de Ségou et Sikasso, par le biais de kits photovoltaïques et mini-réseaux hybrides solaire PV-diesel et sur la base du modèle "Fee for service"	Mali			✓	✓
2014/ 352-393 / 2014/ 352-394	POWER KIOSK: Scaling-Up Rural Electrification in Kenya, Ethiopia and Madagascar	Ethiopia; Kenya; Madagascar	✓			
2014/ 352-925	Somali Energy Transformation (SET) Project	Somalia			✓	
2014/ 352-933	Amélioration des conditions de vie des enfants et de leurs familles grâce à un accès à des services énergétiques modernes, propres et abordables dans 30 communautés pauvres du cercle de Kita au Mali	Mali		✓	✓	
2014/ 353-219	Service d'Électricité Solaire avec des Microréseaux en Afrique / SESMA-Burundi	Burundi				✓
2014/ 353-422	Light Up Liberia	Liberia	✓		✓	✓
2014/ 353-458	Light up our Futures	Liberia				✓
2014/ 353-512	Accès à des services énergétiques modernes et durables au Mali	Mali	✓	✓		
2014/ 355-678	Rural Electrification by Photovoltaic solar systems of 30 secondary schools and 20 clinics	Burundi			✓	