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Sustainable Energy for All

Evaluation of battery storage technologies for sustainable and rural electrification in Sub-Saharan Africa

Authors:
Kristina Hojckova
Jan Jelinek
Madeline Schneider
Nathalie Spittler
Imre Varju

December 13th, 2014

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1. Introduction

This research project deals with the goals of the *Sustainable Energy for All* initiative (SE4ALL). The initiative's objectives cover a wide range of topics. Hence, to narrow down the topic it was decided that in this report the focus lies on the potential of energy storage, as a necessary component of photovoltaic (PV) systems, to provide sustainable electrification and enhance rural development in Sub-Saharan Africa. This topical focus has been chosen due the following reasons:

(1) Sub-Saharan Africa is home of 19 out of 20 countries with the lowest degree of electricity access in the world.[1] Furthermore, the lowest electrification rate overall as well as in rural areas is found in Sub-Saharan Africa, as depicted in table 1.

Electricity access in 2011 - Regional aggregates				
Region	**Population without electricity** millions	**Electrification rate** %	**Urban electrification rate** %	**Rural electrification rate** %
Developing countries	**1.257**	**76,5**	**90,6**	**65,1**
Africa	600	43	65	28
North Africa	*1*	*99*	*100*	*99*
Sub-Saharan Africa	*599*	*32*	*55*	*18*
Developing Asia	615	83	95	75
India	*306*	*75*	*94*	*67*
Rest of developing Asia	*309*	*87*	*95*	*80*
Latin America	24	95	99	81
Middle East	19	91	99	76
Transition economies & OECD	**1**	**99,9**	**100,0**	**99,7**
World	**1.258**	**81,9**	**93,7**	**69,0**

Table 1: Electricity access in 2011[2]

(2) The most flexible and easy form of energy is electricity. In fact, the provision of electricity is loss-free and non-polluting. Additionally, it is weightless, "easier" (less

[1] 'SE4ALL Africa Hub Leaflet' (SE4All website) < http://www.se4all.org/wp-content/uploads/2013/10/SE4ALL-africa-hub-leaflet-web_Feb-2014.pdf> accessed 16 October 2014.

[2] 'Energy access database' (IEA website) <http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/ > accessed 14 October 2014.

dangerously) to transport and distribute. Therefore electricity represents a vital source of energy to meet the goals of the SE4All initiative.[3]

(3) Photovoltaic as a source has been chosen because in Sub-Saharan Africa there is a great potential to make use of solar energy. This becomes especially evident when looking at GIS for sustainable energies.[4]

(4) Storage is an essential part for off-grid electrification with renewable energies but the topic seems to be under-represented in the discussion about sustainable energies for all.

By combining those four aspects, we want to give a broader view on the role of storage in reaching the goal of sustainable energies for all. This will be done by starting to describe the socio-economic effects of energy access programs, especially off-grid electrification, on the population in rural areas, followed by an explanation of the technical factors of storage technologies. From those two parts we want to draw a number of criteria – social, environmental and technological – which storages technologies should meet in order to support sustainable electrification on a technological, environmental and social level. Two storage examples will be presented and compared according to the established criteria, in order to depict the meaning of adding social and environmental criteria, when assessing storage technologies and how those can affect the assessment results.

2. Novelty of the research

Growing interest in renewable energy technologies as well as concerns about climate change and peak oil contributes to the intensified interest in storage technologies as a "critical technological component of the future energy landscape" in energy policy and investment debates.[5] Emanating from a vast literature review, we have identified that the need for renewable energy technologies is unquestionable. However, due to the unpredictability and irregularity in renewable energy generation, we need to deal with the key issue of the storage technologies in order to diminish the intermittent nature of the renewable energy production. Therefore, finding the suitable storage technology brings us closer to tackling the negative aspects of renewable energy technologies, thus making them a feasible alternative to traditional energy technologies.[6]

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[3] IEC, 'Coping with the Energy Challenge; The IEC's role' (2010) 5.

[4] 'Global Atlas for Renewable Energy' (IRENA website) <http://globalatlas.irena.org/> accessed 31 August 2014.

[5] Tugrul U. Daim et al., 'Evaluation of Energy Storage Technologies for Integration with Renewable Electricity: Quantifying Expert Opinions' (2012) Vol. 3 Environmental Innovation and Societal Transitions 30.

[6] Georgina Harell; Tugrul U. Daim, 'Forecasting Energy Storage Technologies' (2009) Vol. 11 No. 6 Foresight 74.

The ultimate motive for choosing the storage technologies evaluation is the apparent gap in complex evaluation of storage technologies in the currently available literature. As most of the literature dealing with energy storage technologies focuses on technological or economic aspects of storage technologies, we decided to choose a more holistic approach in this research paper including social and environmental indicators. Consequently, the aim of this research paper is not only to raise awareness of the importance of storage technologies but more essentially to offer a holistic evaluation of storage technologies in order to emphasize the need of an integrated approach in renewable energy provision.

3. The empowerment of electrification on rural areas and development

Providing energy in general and electricity in particular, is broadly recognized to directly support the achievement of the Millennium Development Goals, as we assume that gaining sustainable access to modern energy technologies facilitates economic and social development and improves the quality of life. However, the area of Sub-Saharan Africa, where only 11 percent of the population uses electricity, is still suffering from low electrification rates.[7] Moreover, energy access is primarily a rural problem. 1.1 billion (out of 1.3 billion or 85%) lacking electricity access are found in rural areas. Likewise, more than 2.2 billion (out of 2.7 billion or 81%) without clean cooking energy access live in rural areas.[8] These disparities are typical for low-income countries, especially in Sub-Saharan Africa.[9]

The essential role of rural electrification to trigger both social and economic development has been widely acknowledged. Yet, in order to achieve successful provision of electricity, it must fulfill certain requirements for the system to be functional in specific settings and sustainable over time. As the research conducted by the World Bank indicates, the key to successful electrification projects may be found outside the framework of market efficiency and of sustainability.[10] As the evidence reveals, providing modern electricity technologies does not automatically lead to development. Thus, integrated development and coordination between actors are needed for access to electricity to achieve economic growth and sustainable development.

[7] Gunther Bensch et al., 'Impacts of rural electrification in Rwanda' (2011) Vol. 3 No. 4 Journal of Development Effectiveness 567.
[8] 'Energy access database' (on IEA website) <http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/ > accessed 14 October 2014.
[9] Subhes C. Bhattacharyya, 'Energy access programmes and sustainable development: A critical review and analysis' (2012) Vol. 16 No. 3 Energy for Sustainable Development 263.
[10] Annabel Yadoo; Heather Cruickshank, 'The value of cooperatives in rural electrification' (2010) Vol. 38 Energy Policy 2941-2942.

As Ahlborg points out, the essential part of the modern renewable energy projects is to invest into capacity training and productive activities and thus support local initiatives and business. Moreover, on the national level, the governments need to focus on strengthening and developing of rural markets, as stable rural market foundations encourage the productivity of the rural communities.[11]

One can find success stories too and although factors might vary from country to country or region to region, impacts of successful energy access seem to exist.[12]

Studies undertaken by anthropologists underline the importance of local specifics for success of technology transfer between societies. For instance Wilkins, concentrates on the technology transfer, particularly on the adoption of diverse small-scale renewable energy technologies in rural areas world-wide. According to Wilkins, the success lies beyond the transfer of the necessary equipment. “The information, skills and knowhow, which are needed to fund, manufacture, install, operate and maintain the equipment” are equally important.[13]

The case of Kenya represents a successful story of the above-mentioned approach.[14] In Kenya, 20.000 to 40.000 PV systems have been installed between 1984 and 1994. This installment was privately financed and brought about a large number of benefits to the population. The electricity generated through the panels was mainly used for lighting purposes, which was the most significant factor for people to take a decision for a PV system, but also for TV and radio. Through electric lighting, well-being was improved due its positive health effects as well as it can support safety. TV and radio offered a “new” opportunity for people to access all sorts of information. The emerging access to electricity furthermore contributed to benefits such as convenience and education.[15] Additionally, education on the technologies was provided and employment opportunities with regards to PV panels arose. Hence, people were capable of handling the technology, creating not only job opportunities but also empowering the communities rather than experts from the “outside”. Nonetheless, expertise and training still need to be increased. Hence, apart from the general benefits, economic motivation was a critical factor for enhancing dissemination of PV in Kenya.[16] Solar panel systems are decentralized and environmentally friendly, use locally available energy sources and are easily transportable, yet

[11] Helene Ahlborg, ‘Electricity for better lives in rural Tanzania and Mozambique – understanding and addressing the challenges’ (2012) Chalmers University of Technology 11-22.
[12] Subhes C. Bhattacharyya, ‘Energy access programmes and sustainable development: A critical review and analysis’ (2012) Vol. 16 No. 3 Energy for Sustainable Development 264-266.
[13] Gill Willkins, *Technology transfer for renewable energy. Overcoming barriers in developing countries* (Earthscan Publications Ltd 2002) 44.
[14] Richard H. Acker; Daniel M. Kammen, 'The Quiet (Energy) Revolution' (1996) Vol. 24 No. 1 Energy Policy 86.
[15] Ibid 100-111.
[16] Ibid 100-104.

most importantly are less expensive than fossil fuels that are vulnerable to severe price fluctuations. As a matter of fact, the price and financing of any energy source remains an essential feature in poor rural areas.[17] Even though, many authors define finance as the principal barrier in achieving sustainable energy access in rural areas, it is certainly not the only barrier. Financing is indeed interconnected with other social and technological implications. Thus, when forming sustainable financing of solar systems, we need to consider the social context and recognize the user's energy requirements and the institutional environment in which the finance operates. Unfortunately, only little attention had been given to consumer finance for the renewable energy technologies in Sub-Saharan Africa. Nevertheless, Rolffs et al. analyze the weaknesses of the past solar finance approaches in Kenya in order to create sustainable approaches for the future. Kenya as the best example of a renewable energy market in Sub-Saharan Africa, driven by the consumer demand for mostly off-grid solar systems, shows only little success in previous financing.[18] Rolffs et al. offer a socio-technical perspective to understand the financing of the solar systems, observing what and in which way local people pay for solar technologies. Consequently, we can identify the previous weaknesses in finance approaches. Among the most significant deficiencies in solar systems financing can be found the limited character of finance to few spheres of the society, leaving the low-income communities without financing opportunities. Furthermore, the low-income class cannot afford solar technologies due to high interest rates, caused by high transaction costs. After the systems have been purchased, the service support for the costumer proves to be often weak, resulting in dissatisfaction and refusing to pay the loan. Likewise, the lack of regulation between actors providing electrification services leads to weak costumer care. In order to avoid these drawbacks in the future there is still a need to strengthen the commitment of the (Kenyan) government to foster national markets and reduce the risks triggered by political instability as well as gain coherent support from international donors to foster the local competitiveness with conventional energy services. Moreover, a thorough market research would contribute to gain better understanding of costumer's income flow and the range of expenditure available to spend on energy.[19]

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[17] Ibid 82.

[18] Paula Rolffs et al.,'Financing Sustainable Energy for All: Pay-as-you-go vs. traditional solar finance approaches in Kenya' (2014) STEPS Working Paper 59 STEPS Centre 1.

[19] Paula Rolffs et al., 'Financing Sustainable Energy for All: Pay-as-you-go vs. traditional solar finance approaches in Kenya' (2014) STEPS Working Paper 59 STEPS Centre 34-35.

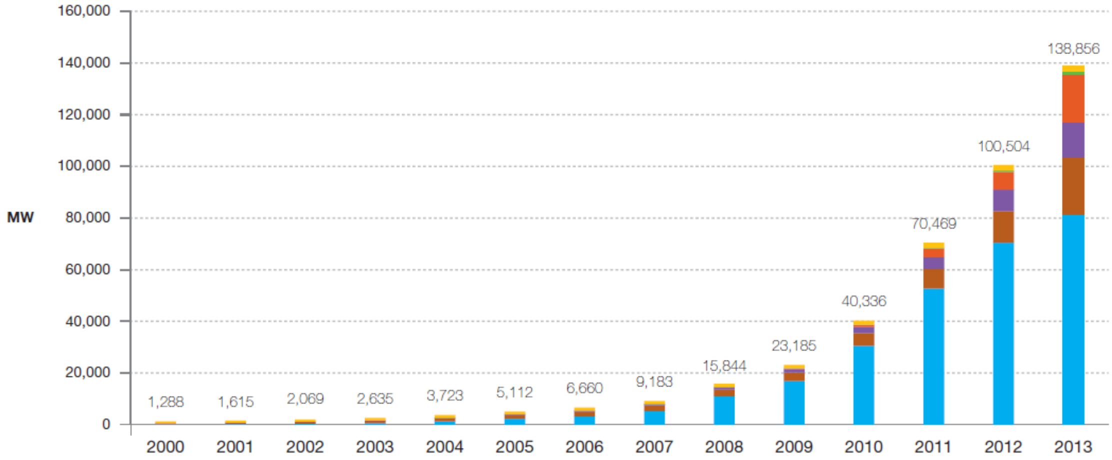
4. The importance of photovoltaic technology and energy storage

In their analysis, Acker and Kammen argued that *"renewable energy systems can assist national energy autonomy, decentralize resource management, promote environmental conservation, and serve as a means to reduce global warming"* but *"battery is normally the weakest link in any domestic PV system, and is the most common cause of failure for photovoltaic systems in East Africa."*[20] Hence, this section deals with the role of the relevant technologies i.e. photovoltaic and storage.

4.1. Photovoltaic

Due to its constantly growing installations during the past decade, PV technology is evolving into one of the major sources for power generation worldwide, see Figure 1. It is true that Europe is the dominant player in the PV market but the rest of the world has great potential to catch up.[21] In Sub-Saharan Africa photovoltaics are a particularly promising energy form as solar is there among the most prominent energy sources.[22] PV power generation is currently the most easily accessible method of acquiring sustainable energy in a considerable part of off-grid areas in Sub-Saharan Africa.[23] It offers a suitable ratio between the price for acquisition and production of electric energy with a conventional payback between 2 to 4 years.[24] Due to these advantages, photovoltaics are suitable for use even in less developed environments. A significant long-term problem is often the environmentally unfriendly production of solar panels, which are additionally almost never locally produced in Sub-Saharan African countries.

[20] Richard H. Acker; Daniel M. Kammen, 'The Quiet (Energy) Revolution' (1996) Vol. 24 No. 1 Energy Policy 81, 101.
[21] EPIA,'Global Market Outlook Photovoltaics 2014-2018' (2014) 17.
[22] 'Global Atlas for Renewable Energy' (IRENA website) <http://globalatlas.irena.org/> accessed 31 August 2014.
[23] Fabio Monforti-Ferrario,'Renewable energies in Africa – current knowledge' (2011) JRC Scientific and Technical Reports 11-13.
[24] Christian Breyer et al.,'Electrifying The Poor: Highly Economic Off-Grid PV Systems in Ethiopia – A Basis For Sustainable Rural Development' (2011) 2.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
RoW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	80	205	570	953
China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,600
Americas	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,727
APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
Europe	129	265	399	601	1,306	2,291	3,289	5,312	11,020	16,854	30,505	52,764	70,513	81,488
Total	**1,288**	**1,615**	**2,069**	**2,635**	**3,723**	**5,112**	**6,660**	**9,183**	**15,844**	**23,185**	**40,336**	**70,469**	**100,504**	**138,856**

RoW: Rest of the World. MEA: Middle East and Africa. APAC: Asia Pacific.
Methodology used for RoW data collection has changed in 2012.

Figure 1: Evolution of global photovoltaic cumulative installed capacity 2000-2013[25]

Comparison with other technologies

Solar power has the greatest advantage compared to other technologies when it comes to implementation costs. It is in most cases the cheapest environmentally friendly solution suitable for off-grid installation in the majority of Sub-Saharan African regions.

Wind energy constitutes one of the most prominent renewable energy forms at present, however the construction of wind power systems is often far more expensive compared to solar energy. Its significant weakness is also the unpredictable nature of wind, which inevitably poses great demands on buffer and transfer capacity to the power grid. Battery storage of energy created in wind power plants is currently almost beyond the technological possibilities and wind power is therefore often unsuitable for off-grid areas. Wind energy can however be a promising alternative in the next decade even for off-grids due to advances in research showing the possibility of application of high-technology solutions as sodium-sulfur or nickel chloride batteries.[26]

A significant part of the energy portfolio of Sub-Saharan countries such as the Democratic Republic of the Congo consists of hydropower. Hydroelectric power is nevertheless practically

[25] EPIA,'Global Market Outlook Photovoltaics 2014-2018' (2014) 17.

[26] Nic Sharpley, 'Unlocking the potential of wind power with energy storage' (Wind power engineering & development website) < http://www.windpowerengineering.com/design/unlocking-potential-wind-power-energy-storage/> accessed 28 August 2014.

never appropriate for Sub-Saharan rural off-grid areas as large-scale hydro projects tend to be too expensive and environmentally unacceptable while small-scale projects need advanced technologies with stable service.[27]

Bioenergy is often regarded as a very promising energy form for off-grid areas in Sub-Saharan Africa. However, there exist serious difficulties to ensure stable supply of biomass.[28]

4.2. Storage

The storage of electricity is one of the most crucial issues and weakest link of PV technology and renewable energy in general. This is due to the fact that photovoltaics have the ability to produce more electricity than needed for consumption through the sunny day, however their production capacity rapidly decreases by sunset. In other words, the power fluctuates independently from demand.[29] That is why, energy storage systems are highly essential, especially in isolated areas.

Solar energy storage methods can be classified into two forms i.e. electricity storage and thermal energy storage. We focus on electricity storage as it is of primary concern for Sub-Saharan Africa. There exist various types of electricity storage systems that differ by stages of development and applicability. Currently, the most mature ones are Pumped Storage Hydropower (PSH), Compressed Air Energy Storage (CAES), Flywheel energy storage as well as batteries, in particular lead-acid, sodium-sulphur and lithium-ion batteries. Figure 2 shows the systems that are currently in use. Even though PSH is by far the most dominant electricity storage system, batteries are best used for remote areas.[30] This is due to their autonomy as well as their ratio between performance and cost. Their lifetime is however limited and they carry potential risks for the environment.[31]

[27] Thomas Buchholz; Izael Da Silva, 'Potential of distributed wood-based biopower systems serving basic electricity needs in rural Uganda' (2010) Vol. 14 Energy for Sustainable Development 57.
[28] Stephen Karekezi; Waeni Kithyoma, 'Renewable energy development' (2003) The Workshop for African Energy Experts on Operationalizing the NEPAD Energy Initiative 8-14.
[29] Hussein Ibrahim et al. 'Energy Storage Systems – Characteristics and comparisons' (2008) Vol. 12 No. 5 Renewable and Sustainable Energy Reviews 1223.
[30] IEA, 'Technology Roadmap: Energy Storage' (2014) 16-17.
[31] Hussein Ibrahim et al. 'Energy Storage Systems – Characteristics and comparisons' (2008) Vol. 12 No. 5 Renewable and Sustainable Energy Reviews 1247.

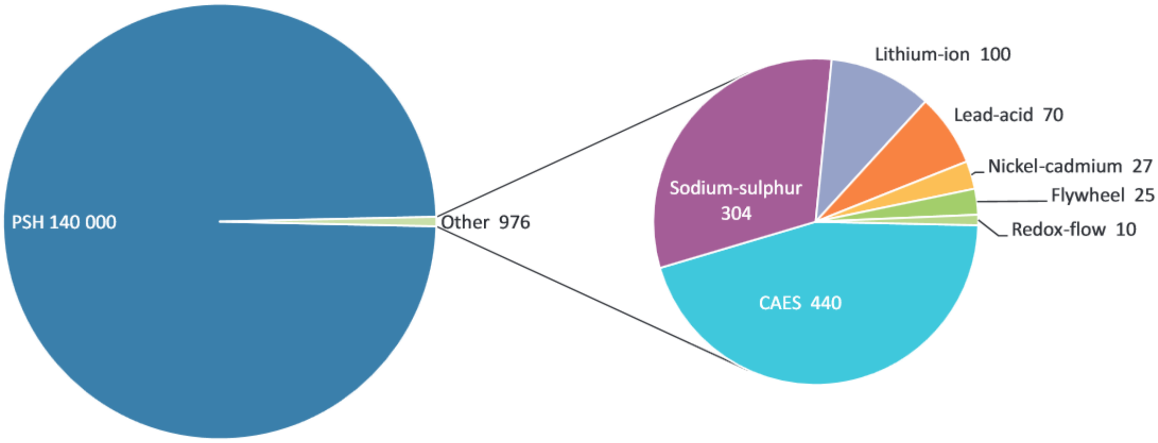


Figure 2: Electrical Energy Storage Technology Options[32]

5. Selection and definition of indicators

On the one hand, most definitions of sustainable development include an environmental, social and economic aspect (e.g. Brundtlandt Report). On the other hand, electrification technology evaluations usually are only concerned with the technological and economic aspects of the various technologies. For achieving sustainable development through technological innovation means that technology and sustainable development are combined and so needs to be their evaluation. Although some studies deal with the environmental and social effects of energy access programs and different energy systems[33], those aspects find little attention when different storage technologies are evaluated. As storage is one of the most crucial elements for sustainable electrification, it is important to assess the current technologies in order to be able to compare them and depict deficiencies, which can be improved once found. Hence, the evaluation of storage technologies should also be a holistic one as it might show deficiencies on different levels (social, environmental), which are not evident if only technological and economic aspects are thought of but can hinder their effective implementation later on. That is why, in this part of the paper technological, socio-economic as well as environmental indicators are identified which are then applied to specific battery storage technologies in the subsequent section.

[32] IEA, 'Technology Roadmap: Energy Storage' (2014) 17.
[33] Rahman K. Akikur et al., 'Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review' (2013) Vol. 27 Renewable and Sustainable Energy Reviews 738-752.

5.1. Technological indicators

5.1.1. Energy efficiency

This indicator refers to the efficiency of the converting process of the energy between production plant, storage and appliances. This process should be as efficient as possible with as little losses of energy as possible.

5.1.2. Storage capacity

Storage capacity is an indicator, which deals with the capacity of energy that can be stored for a certain period of time. Depending on the electricity needs of people during certain times of the day the needed capacity might vary. In general storage capacity is quite low at the moment.

5.1.3. Safety

Safety depends on a couple of factors, which are the following: materials used in terms of their quality, materials used in terms of their reactiveness and the quality of the construction of the overall storage plant.

5.2. Socio-economic indicators

5.2.1. Empowerment

Empowerment can exist in social, economic and political dimension and it can be found on an individual or collective level.[34] The provision of modern electricity in poor rural areas creates opportunities, improve the quality of life and support development on a variety of socio-economic levels.[35] Individuals and communities that have access to relevant, timely and understandable information can grasp opportunities, negotiate, ensure accountability of state actors, exercise their rights and reach services.[36] As PV systems are mostly used for lighting, television or radio functioning, people receive most current information from all over the world.[37]

Economic empowerment in terms of rural market and entrepreneurship development is crucial for the welfare in poor rural areas in Sub-Saharan Africa. Economic development of rural areas cannot be maintained unless the local actors are engaged in productive activities.[38]

[34] World Bank, 'Empowerment and Poverty Reduction: a Sourcebook' (2002) 10-11.
[35] Shahidur R. Khandker et al., 'Who Benefits Most From Rural Electrification? Evidence in India' (2012) Policy Research Working Paper 6095 2.
[36] World Bank, 'Empowerment and Poverty Reduction: a Sourcebook' (2002) 15.
[37] Richard H. Acker; Daniel M. Kammen, 'The Quiet (Energy) Revolution' (1996) Vol. 24 No. 1 Energy Policy 105.
[38] World Bank, 'Empowerment and Poverty Reduction: a Sourcebook' (2002) 42.

Recently, a direct correlation between electrification and women's positioning has been proven. According to Raub, access as well as lack of electrification implies different consequences for men and women. As the prevailing patriarchal system in the developing world keeps the women at home to take care of the households, they tend to be more affected by ineffective energy services. For that reason, energy access can dismantle burdens laying on women's shoulders and offer productive time for women.[39]

5.2.2. Involvement

According to Hughes, power systems evolve as a correlation between technology and society.[40] The importance of this correlation appears once the technology has been implemented. In this stage, many factors that hinder the sustainability of electrification arise. Despite the fact that solar energy is easily installable and maintained, lack of practical support for users of the off-grid technology is common in a sense of lacking local manufacturing of the required equipment and lack of skilled personnel able to install and maintain these energy technologies. The root of the problem is ineffective coordination between governmental departments that disable the necessary trainings to reach the local users.[41]

5.2.3. Affordability

Renewable energy technologies should be financially feasible as well as financially affordable.[42] In other words, the most essential sustainability indicator for electrification is to offer cost effective and affordable provision of energy at present as well as in future. Renewable energy implementation requires considering cost effectiveness and at the same the initial as well as operating cost burden that remains on the user's shoulders. Additionally, considering the availability of financial support for these systems is important.[43]

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[39] Viviane Raub, 'Rural Electrification in Senegal: Access to Electricity and its Impacts on Women's Needs' (2013) Student publication for Master's degree 9.; Helene Ahlborg; Linus Hammar, 'Drivers and barriers to rural electrification in Tanzania and Mozambique - grid-extension, off-grid, and renewable energy technologies' (2014) Vol. 61 Renewable Energy 120.

[40] Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (JHU Press 1993) 2.

[41] Judith Alazraque-Cherni, 'Renewable Energy for Rural Sustainability in Developing Countries' (2008) Vol. 28 No. 2 Bulletin of Science, Technology & Society 109-110.

[42] Wahidul K. Biswas et al., 'Model for empowering rural poor through renewable energy technologies in Bangladesh' (2001) Vol. 4 No. 6 336.

[43] Subhes C. Bhattacharyya 'Energy access programmes and sustainable development: A critical review and analysis' (2012) Vol. 16 No. 3 Energy for Sustainable Development 269.

5.3. Environmental indicators

5.3.1. Hazards

As we progress towards a sustainable economy, it has to be understood that this development is not without risks. The different storage technologies have to be dealt with care, because they have some possibly negative effects too, for example toxicity or corrosivity. They affect human health directly as well as indirectly through soil and waters. The negative impacts upon natural environment and human health should be taken into account by this indicator.

5.3.2. Conservation/ preservation

Storage technologies could play a serious role in environmental conservation and help to preserve what is left in the natural environment surrounding us. Contemporary efforts to substantially reduce CO_2 emissions and the proportion of fossil fuels in electricity generation are creating cleaner and low-carbon economies. Therefore, the proportion of renewable energy sources has to be extended respectfully and storage mechanisms should be taken into consideration. The usage of wood as an energy source is still considerably high in Sub-Saharan Africa, which combined with a steady increasing population leads to a rapid deforestation. As storage mechanisms are connected to renewable energy sources, their ability to substitute fossil and wood fuels should be also examined.

5.3.3. Avoidance/ prevention

Sustainable development requires not only to conserve the natural environment around us, but also to prevent its further contamination. Storage technologies have to be handled with great care in order to function as environmentally friendly as possible. Waste management systems should be able to effectively deal with hazardous materials, avoiding much of the possibility that highly polluting materials are stuck with household waste, and landing in municipal landfills or trash incinerators. Therefore, recyclability of probable waste plays an important role. Recycling of used materials, besides that it is eco-friendly, contributes to rationalize the use of limited resources, although recycling in general can be much more costly than exploiting new resources. Serious contributions from manufacturers are also needed, which could be for example a system for recycling including drop-off points and recycling plants. The adequate awareness should be raised in commercial and residential areas as well. Thus, the recyclability of the chosen storage technologies, their efficiency as well as their lifetime should be analyzed.

6. Comparison of storage technologies according to selected indicators

As stated earlier, battery storage technologies are best suited for off-grid areas, in particular lead acid and lithium-ion batteries. Both types offer benefits as well as drawbacks. The lead acid battery technology is the most developed battery type and comparatively inexpensive. It represents a good compromise between cost and performance. Nevertheless, it is rather short-lived, unreliable and heavy. What is more, lead acid batteries consist of highly toxic materials and can thus create environmental hazards. The lithium-ion battery, by comparison, is considered to be the most promising battery storage option due to its light weight and high performance. Nevertheless, its early development stage is linked to high costs.[44]

With the help of the indicators identified in the previous section, both battery storage types are compared in the course of this part in order to identify which technology offers the greatest opportunity for improvement in rural electrification and development in Sub-Saharan Africa. The different aspects are ranked through a scale from 1 (low potential for rural development) to 3 (high potential for rural development). At the end of this part, the total sum of the indicators will show which battery storage type is more suitable to increase energy access in off-grid areas. As the technologies are evaluated not only from a technical but also a socio-economic and environmental viewpoint, a holistic analysis is possible.

6.1. Technological indicators

6.1.1. Energy efficiency

Lead acid battery

When analyzing energy efficiency, the whole cycle of a battery has to be taken into consideration, including charging, storing the charge and discharging.[45] Commercially in use since the 1890s, the lead acid battery is the most mature battery technology with a high energy efficiency rate ranging between 70 to 90%.[46] In terms of discharge, it performs also quite well with an average of 80%.[47] It is true that its capacity is lowered when high power has to be discharged but this drawback is not of great importance for rural areas.[48]

[44] Yu Hou et al. 'Solar Energy Storage Methods' (2011) Vol. 50 I&EC 8957, 8963; Hussein Ibrahim et al. 'Energy Storage Systems – Characteristics and comparisons' (2008) Vol. 12 No. 5 Renewable and Sustainable Energy Reviews 1244-1249.
[45] Helder L. Ferreira et al., 'Characterisation of electrical energy storage technologies' (2013) Vol. 53 Energy 292.
[46] Haisheng Chen et al., 'Progress in electrical energy storage system: A critical review' (2009) Vol. 19 Progress in Natural Science 297.
[47] Yu Hou et al., 'Solar Energy Storage Methods' (2011) Vol. 50 I&EC Research 8958.
[48] IEC, 'Electrical Energy Storage' (2011) White paper 24.

Lithium-ion battery

As the lithium-ion battery is very performant with an efficiency that is able to reach 100%, it is considered to be a storage technology with great future potential.[49] Similarly to the lead acid battery, it is capable of discharging 80% of the stored energy.[50]

6.1.2. Storage capacity

Lead acid battery

The lead acid battery is able to store energy over a period of several days which is sufficient for isolated areas with high solar irradiation like in Sub-Saharan Africa. Nevertheless, the capacity is significantly lower than the one of PSH or CAES storage technologies. During the storage process, the standby losses of the lead acid battery are very low, namely 0.1-0.3%, which underlines its efficiency.[51]

Lithium-ion battery

The storage patterns of the lithium-ion battery are pretty similar to the one of the lead acid battery, except for the fact that the former is capable of discharging energy almost at any time ranging from seconds to weeks. This aspect makes the lithium-ion battery very flexible and adaptable to specific conditions.[52]

6.1.3. Safety

Lead acid battery

Lead dioxide, lead and sulphuric acid are essential components of this battery type and thus, make it environmentally unfriendly but also robust.[53] For instance, the lead acid battery is able to operate under extreme temperatures that range from -30 to +50 degrees. Due to its robustness, its efficiency as well as its maturity, the lead acid battery is a very reliable and safe storage technology.[54]

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[49] Haisheng Chen et al., 'Progress in electrical energy storage system: A critical review' (2009) Vol. 19 Progress in Natural Science 298.
[50] Yu Hou et al., 'Solar Energy Storage Methods' (2011) Vol. 50 I&EC Research 8958.
[51] Haisheng Chen et al., 'Progress in electrical energy storage system: A critical review' (2009) Vol. 19 Progress in Natural Science 307.
[52] IEC, 'Electrical Energy Storage' (2011) White paper 25.
[53] Ioannis Hadjipaschalis et al., 'Overview of current and future energy storage technologies for electric power applications' (2009) Vol. 13 Renewable and Sustainable Energy Reviews 1515.
[54] Alliance for Rural Electrification, 'Using batteries to ensure clean, reliable and affordable universal electricity access – A guide for energy decision makers' (2013) Position paper – Energy Storage Campaign 2013 3.

Lithium-ion battery

A lithium-ion battery is, amongst others, made of cathode material that is comparatively inexpensive. However, special packaging is needed as this battery type tends to overheat at high temperatures due to thermally unstable metal oxide electrodes. A voltage balance circuit as well as a monitoring unit are needed in order to control the voltage level and circumvent over charging and over discharging. These measures increase the costs drastically.[55] In general, the technology is commercially produced since 1990 and already well established in the small portable device market. This factor and the elevated energy efficiency ensure reliability.[56]

6.2. Socio-economic indicators

6.2.1. Empowerment

Lead acid battery

The addition of batteries to PV systems can contribute to the empowerment of local communities through a variety of ways. The focus lies on specific factors of access to information, business opportunities and women's empowerment as these can be regarded crucial in the rural environment of Sub-Saharan Africa. The lead acid battery is considered to be a matured technology making up the bulk of existing installations in the developing world, as both flooded and valve-regulated lead-acid batteries (VRLA) types are applicable on remote sites.[57] The flooded type is appropriate for the empowerment of rural areas with a regular maintenance. The gelled electrolyte type may be considered equally appropriate with a preferably less maintenance.[58] Both of these types are able to provide enough power for ordinary home or rural activities and basic business operations. They can therefore sufficiently contribute to all three factors only with limits for high power consumptions.

Lithium-ion battery

The lithium-ion battery is a relatively new and advanced technology compared with the lead acid. It however provides virtually the same advantages in the light of rural empowerment. Lithium-ion batteries are better suited for long-term storage, and one of their strengths is also a

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[55] Teuku M. I. Mahlia et al., 'A review of available methods and development on energy storage; technology update' (2014) Vol. 33 Renewable and Sustainable Energy Reviews 538.; IEC, 'Electrical Energy Storage' (2011) White paper 25.

[56] Haisheng Chen et al., 'Progress in electrical energy storage system: A critical review' (2009) Vol. 19 Progress in Natural Science 298.

[57] EUROBAT, 'Battery Energy Storage for Rural Electrification Systems' (2013) Guidance Document 15.

[58] EPM, 'Valve-Regulated Lead-Acid (VRLA): Gelled Electrolyte (gel) and Absorbed Glass Mat (AGM) Batteries' (2012) 1-8.

greater capacity.[59] Given that their price is still several times higher than in the case of lead-acid type, their benefits for a rural empowerment offset. The lithium-ion battery is appropriate with regard to all three factors and can also deliver higher electrical current needed for energy-consuming activities without damaging the storage system.[60]

6.2.2. Involvement

Lead acid battery

Lead acid batteries are globally produced and subsequently installed in the destination with the help of foreign experts. The local population should be trained in the use and maintenance of the battery system in the best scenario, although the PV storage system is often launched without an adequate concern for securing a stable local service base. Lead acid storage technology requires regular servicing and controls, which are in the case of the flooded type battery frequently necessary and even the VRLA batteries need occasional servicing.[61]

Lithium-ion battery

The process of lithium-ion storage system implementation is realized similarly to the lead acid battery case. Lithium-ion technology is maintenance free, although it requires advanced monitoring of cell temperature and balancing in contrast with lead acid battery types. Lithium-ion battery systems are often remotely controlled without the necessity of regular visits to the site.[62] Lithium-ion storage systems entail the possibility of attractive involvement of local experts, although require greater demands on the expertise of these operators.

6.2.3. Affordability

Lead acid battery

The possibly greatest advantage of lead acid batteries is their low price compared to other battery types. They provide a reasonable payback ratio and can thus be acquired even without external subsidies. Lead acid battery can also be installed for a single rural or remote house outside the complex storage system. The price of small storage systems may start from approximately 400 US dollars depending on the type and complexity of the devices.[63]

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[59] Andreas Jossen; Margret Wohlfahrt-Mehrens, 'Overview on current status of lithium-Ion batteries' (2007) Second International Renewable Energy Storage Conference 19 - 21 November 2007 Bonn/Germany 11-29.

[60] Hussein Ibrahim et al. 'Energy Storage Systems – Characteristics and comparisons' (2008) Vol. 12 No. 5 Renewable and Sustainable Energy Reviews 1244-1249.

[61] EXIDE, 'Gel-VRLA-Batteries' (2004) 16-40.

[62] Alliance for Rural Electrification, 'Using batteries to ensure clean, reliable and affordable universal electricity access – A guide for energy decision makers' (2013) Position paper – Energy Storage Campaign 2013 3.

[63] 'Deep Cycle Batteries' (Ecodirect website) <http://www.ecodirect.com/Deep-Cycle-Battery-s/5.htm> accessed 26 October 2014.

Lithium-ion battery

Due to the special packaging that is needed to prevent the battery from a thermal runaway, the price of a lithium-ion battery is severalfold higher than the price of a lead acid type. Until now, it is suitable for rural Sub-Saharan areas rather in the presence of external funding or in specific cases when advantages of this technology are essential.[64] Nevertheless, there is on-going research to involve other cheaper materials that will reduce the price of this battery type.

6.3. Environmental indicators

6.3.1. Hazards

Lead acid battery

The chemical composition of the lead acid battery poses serious threats to the environment and the human health. Lead is a toxic metal and sulphuric acid is highly corrosive. These substances can contaminate soil and groundwater as well as severely affect human health if they are exposed from the protective battery container. This might occur due to improper recycling or through abandoning them in the outdoors.[65]

Lithium-ion battery

It is estimated that lithium-ion batteries are about half as toxic as lead acid batteries, but they still can significantly affect the environment and the human health. Their toxicity is associated primarily with chromium, lead, cobalt, thallium and other specific substances.[66] Certain danger can also be connected with the lack of awareness of the lithium-ion battery substances.

6.3.2. Conservation/ preservation

Lead acid battery

The lead acid battery type contributes to environmental conservation as well as to greenhouse gas emissions reduction when applying the storage system. This is attained through diverse positive effects like elimination of the need for diesel generators or the consumption of firewood in rural settlements. Significant danger for the environment is however linked to a possible improper treatment of the battery during or especially after its lifetime.

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[64] IEC, ‘Electrical Energy Storage’ (2011) White paper 25.

[65] Pascal Haefliger et al. ‘Mass Lead Intoxication from Informal Used Lead-Acid Battery Recycling in Dakar, Senegal’ (2009) Vol. 117 No. 10 Environmental Health Perspectives 1535-1540.

[66] Daniel Hsing Po Kang et al. ‘Potential Environmental and Human Health Impacts of Rechargeable Lithium Batteries in Electronic Waste’ (2013) Vol. 47 No. 10 Environmental Science and Technology 5495–5503.

Lithium-ion battery

The lithium-ion battery type has similar positive effects on the environment as the lead acid battery. The production of the lithium-ion battery performs badly in terms of greenhouse gas emissions, which is quite contrary to its less negative effects on local environment.[67]

6.3.3. Avoidance/ prevention

Lead acid battery

The lead acid battery has a comparatively short cycle life of 500 to 1000 cycles as well as a relatively short lifetime of 5 to 15 years.[68] Nevertheless, the recycling efficiency is very high with more than 95%.[69] This is due to the fact that the environmental hazards of lead acid batteries have led to the creation of specific regulations for their disposal. Therefore, this battery type belongs to the most recycled products worldwide. For instance, 93.3% of all lead batteries were recycled in 1999.[70]

Lithium-ion battery

Due to material improvements, the lithium-ion battery can reach nowadays a life cycle of up to 10.000 cycles which outperforms the number of most other battery types.[71] It is true that the lithium-ion battery has on average the same lifetime as the lead acid battery but the former ages faster under high temperatures. This is because the special packaging and the materials used make it fragile.[72] In terms of recycling, it reaches an efficiency of 50% as the lithium oxides and salts can be reclaimed.[73]

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67 'Environmental impacts of batteries for low carbon technologies compared' (Science for Environment Policy) <http://ec.europa.eu/environment/integration/research/newsalert/pdf/303na1.pdf > accessed 25 October 2014.

68 Haisheng Chen et al., 'Progress in electrical energy storage system: A critical review' (2009) Vol. 19 Progress in Natural Science 308.

69 Alliance for Rural Electrification, 'Using batteries to ensure clean, reliable and affordable universal electricity access – A guide for energy decision makers' (2013) Position paper – Energy Storage Campaign 2013 3.

70 EPRI, 'EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications' (2003) Final report 6-23.

71 Haisheng Chen et al., 'Progress in electrical energy storage system: A critical review' (2009) Vol. 19 Progress in Natural Science 308.

72 Ioannis Hadjipaschalis; Andreas Poullikkas; Venizelos Efthimiou, 'Overview of current and future energy storage technologies for electric power applications' (2009) Vol. 13 Renewable and Sustainable Energy Reviews 1516.

73 Teuku M. I. Mahlia; Tengku J. Saktisahdan; A. Jannifar; Masjuki H. Hasan; Hendrik S. C. Matseelar, 'A review of available methods and development on energy storage; technology update' (2014) Vol. 33 Renewable and Sustainable Energy Reviews 538.

7. Analysis of findings

In the course of the previous section, the technological, socio-economic and environmental impacts of the lead acid battery as well as of the lithium-ion battery have been identified and evaluated on a scale from 1 (low capability for rural development) to 3 (high capability for rural development). The results obtained through the application of the indicators are summarized in table 2.

Application of indicators - Results		
Criteria	**Lead acid battery**	**Lithium-ion battery**
Technological indicators	**7**	**8**
Energy efficiency	2	3
Storage capacity	2	3
Safety	3	2
Socio-economic indicators	**9**	**6**
Empowerment	3	3
Involvement	3	2
Affordability	3	1
Environmental indicators	**6**	**5**
Hazards	1	2
Conservation	3	2
Avoidance	2	1
Overall results	**22**	**19**

Table 2: Summary of the results obtained through the application of indicators[74]

The findings provide valuable insights into the benefits but also deficits of both battery types. Whereas the lead acid battery performs better from a socio-economic and environmental viewpoint, the lithium-ion battery offers technological advantages. The greatest difference is visible on the socio-economic level where the lithium-ion battery possesses clear deficits due to its high costs. That is why, it received the lowest score of 1. What is more, the lithium-ion battery requires advanced monitoring and expertise during its lifetime. The lead acid battery type, in contrast, obtains the highest possible score across all socio-economic categories.

[74] Own creation

Regarding the technological component, both battery types are well-engineered for the off-grid conditions in Sub-Saharan Africa. The lithium-ion battery scores a slight advantage due to its high performance in energy efficiency and storage capacity which makes it very flexible and adaptable.

The environmental impact of the storage technologies has to be examined carefully as the lowest scores are achieved in this category. It is true that the lead acid and lithium-ion battery contribute to the preservation of the environment as they both save greenhouse gas emissions. Moreover, the lead acid battery can be recycled almost twice as efficiently as the lithium-ion type and is therefore ranked better. Nevertheless, these batteries are still able to create environmental harm due to their partial composition of toxic substances.

To sum up, the lead acid battery receives higher overall results with significant advantages across the socio-economic indicators. Its maturity, affordability and recyclability are some of the lead acid battery's most essential benefits over the lithium-ion battery. As the findings demonstrate that the lead acid battery performs well across most indicators, this type possesses the greatest potential to enhance rural as well as sustainable development in Sub-Saharan Africa. In order to improve rural electrification, not only the allocation of lead acid batteries is necessary but also the involvement of the community in the process.

The development of technology, especially of clean energy, is ongoing and thus, continuous evaluation of promising storage types with the help of the selected indicators is necessary. At the current state, lead acid batteries offer the greatest opportunities for the enlargement of energy access in Sub-Saharan Africa but existent storage technologies might be improved or new technologies developed. For instance, the lithium-ion battery has great potential if its shortcomings including affordability and recyclability are enhanced. What is more, the start-up Aquion Energy from Pittsburgh, US currently works on storage batteries for off-grid areas that are made of recycled materials from food and pharmaceutical industries.[75] If this battery type proofs to perform successfully, it will have the ability to enhance rural development even more due to the reduction of environmental impact.

[75] 'Off-grid & Microgrids' (Aquion Energy website) <http://www.aquionenergy.com/microgrid-energy-storage> accessed 26 November 2014.

8. Conclusion

The focus of this paper was to point to the relevant factors that play a crucial role for making sustainable energies for all possible by looking at one of the key technologies i.e. storage. Hence, assessing and analyzing various energy storage mechanisms - in a chosen part of the world - based on a holistic approach, including not just technological, but socio-economic and environmental factors, too. Thereby, the aim was a comprehensive study, which deals with one of the most pressing issues of our age, the question of energy.

The two main aspects discussed in this paper are:

(i) Storage as an essential and invaluable part of any systems that consist of renewable energy sources, because it is a necessary condition for a renewable energy system to run efficiently, especially off-grid. Unfortunately, so far, this topic does not get as much attention as it should.

(ii) Energy deficiency and low electrification rates in Sub-Saharan Africa are problems which should be resolved at a high priority. It should not be forgotten that the aforementioned problems are connected to a lot of other issues. For example that the lack of energy thwarts any attempts to effectively improve economic capacity and efficiency, as well as certain aspects of social development.

Research showed that in Sub-Saharan rural areas one of the most viable, promising and competitive renewable energy sources is PV technology. By not just considering natural endowments but also financial questions, accessibility and efficiency the study found that in rural areas PV energy is among the best choices to invest in. Still, it should not be forgotten that prevailing structures and energy systems (e.g. diesel) often make it the less attractive choice and that PV energy production is highly dependent on functional storage, which allows the use of produced energy when it is really demanded.

In order to enhance storage development suitable for Sub-Saharan African rural areas not only technological aspects but also others need to be improved. Therefore, two chosen types of storage technologies were compared according to specific indicators, which were formulated according to the results of the research on socio-economic and environmental factors important for sustainable development in less developed regions. The indicators and the evaluation of the chosen storage technologies were based on a vast and profound literature review.

As for the rural application of PV technologies battery storage was considered best due to different factors.

The comparison depicted that the lead-acid battery is more suited in enhancing sustainable rural development. The key factors for this are the maturity of the technology, as well as its affordability and high recyclability. But to ensure that the social and environmental advantages of this battery type really come into effect, an appropriate and functional service and recycling network is of key importance.

Our findings evaluated the most promising and current types of storage, but the development of more and more advanced forms of storage are crucial. In the near future it is possible that the results of this paper will become obsolete, as existing battery technologies could improve greatly and new technologies could arise (e.g. batteries made from recycled materials). However, also new technologies should be assessed using a broader range of indicators than their technological performance, in order to assure their suitability for increasing sustainable development through electrification in the areas most needed. The indicators developed in this paper can provide a basis for evaluation of future development.

9. References

Richard H. Acker; Daniel M. Kammen, 'The Quiet (Energy) Revolution' (1996) Vol. 24 No. 1 Energy Policy 81-111.

Helene Ahlborg; Linus Hammar, ‘Drivers and barriers to rural electrification in Tanzania and Mozambique - grid-extension, off-grid, and renewable energy technologies’ (2014) Vol. 61 Renewable Energy 117-124.

Helene Ahlborg, ‘Electricity for better lives in rural Tanzania and Mozambique – understanding and addressing the challenges’ (2012) Chalmers University of Technology 1-62.

Rahman K. Akikur; Rahman Saidur; Hew W. Ping; Khan R. Ullah, ‘Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review’ (2013) Vol. 27 Renewable and Sustainable Energy Reviews 738-752.

Alliance for Rural Electrification, ‘Using batteries to ensure clean, reliable and affordable universal electricity access – A guide for energy decision makers’ (2013) Position paper – Energy Storage Campaign 2013.

Gunther Bensch; Jochen Kluve; Jörg Peters ‘Impacts of rural electrification in Rwanda’ (2011) Vol. 3 No. 4 Journal of Development Effectiveness 567-588.

Subhes C. Bhattacharyya ‘Energy access programmes and sustainable development: A critical review and analysis’ (2012) Vol. 16 No. 3 Energy for Sustainable Development 260-271.

Wahidul K. Biswas; Paul Bryce; Mark Diesendorf, ‘Model for empowering rural poor through renewable energy technologies in Bangladesh’ (2001) Vol. 4 No. 6 333-344.

Christian Breyer; Alexander Gerlach; Markus Hlusiak; Christian Peters; Peter Adelmann; Jakob Winiecki; Harald Schützeichel; Samson Tsegaye; Workeneh Gashie, ‘Electrifying The Poor: Highly Economic Off-Grid PV Systems in Ethiopia – A Basis For Sustainable Rural Development’ (2011).

Thomas Buchholz; Izael Da Silva, ‘Potential of distributed wood-based biopower systems serving basic electricity needs in rural Uganda’ (2010) Vol. 14 Energy for Sustainable Development 56-61.

Haisheng Chen; Thang N. Cong; Wei Yang; Chunqing Tan; Yongliang Li; Yulong Ding ‘Progress in electrical energy storage system: A critical review’ (2009) Vol. 19 Progress in Natural Science 291-312.

Tugrul U. Daim; Xin Li; Jisun Kim; Scott Simms 'Evaluation of Energy Storage Technologies for Integration with Renewable Electricity: Quantifying Expert Opinions' (2012) Vol. 3 Environmental Innovation and Societal Transitions 29-49.

‘Deep Cycle Batteries’ (Ecodirect website) <http://www.ecodirect.com/Deep-Cycle-Battery-s/5.htm > accessed 26 October 2014.

'Energy access database' (on IEA website) <http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/ > accessed 14 October 2014.

'Environmental impacts of batteries for low carbon technologies compared' (Science for Environment Policy) <http://ec.europa.eu/environment/integration/research/newsalert/pdf/303na1.pdf > accessed 25 October 2014.

EPIA, 'Global Market Outlook Photovoltaics 2014-2018' (2014).

EPM, 'Valve-Regulated Lead-Acid (VRLA): Gelled Electrolyte (gel) and Absorbed Glass Mat (AGM) Batteries' (2012).

EPRI, 'EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications' (2003) Final report.

EUROBAT, 'Battery Energy Storage for Rural Electrification Systems' (2013) Guidance Document.

EXIDE, 'Gel-VRLA-Batteries' (2004).

Helder L. Ferreira; Raquel Garde; Gianluca Fulli; Wil Kling; Joao P. Lopes 'Characterisation of electrical energy storage technologies' (2013) Vol. 53 Energy 288-298.

'Global Atlas for Renewable Energy' (IRENA website) <http://globalatlas.irena.org/> accessed 31 August 2014.

Ioannis Hadjipaschalis; Andreas Poullikkas; Venizelos Efthimiou, 'Overview of current and future energy storage technologies for electric power applications' (2009) Vol. 13 Renewable and Sustainable Energy Reviews 1513-1522.

Pascal Haefliger; Monique Mathieu-Nolf; Stephanie Lociciro; Cheikh Ndiaye; Malang Coly; Amadou Diouf; Absa Lam Faye; Aminata Sow; Joanna Tempowski; Jenny Pronczuk; Antonio Pedro Filipe Junior; Roberto Bertollini; Maria Neira, 'Mass Lead Intoxication from Informal Used Lead-Acid Battery Recycling in Dakar, Senegal' (2009) Vol. 117 No. 10 Environmental Health Perspectives 1535-1540.

Georgina Harell; Tugrul U. Daim, 'Forecasting Energy Storage Technologies' (2009) Vol. 11 No. 6 Foresight 74-85.

Yu Hou; Ruxandra Vidu; Pieter Stroeve, 'Solar Energy Storage Methods' (2011) Vol. 50 Industrial & Engineering Chemistry Research 8954-8964.

Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (JHU Press 1993).

Hussein Ibrahim; Adrian Ilinca; Josee Perron, 'Energy Storage Systems – Characteristics and comparisons' (2008) Vol. 12 No. 5 Renewable and Sustainable Energy Reviews 1221-1250.

IEA, 'Technology Roadmap: Energy Storage' (2014).

IEC, 'Electrical Energy Storage' (2011) White paper.

IEC, 'Coping with the Energy Challenge; The IEC's role' (2010).

Andreas Jossen; Margret Wohlfahrt-Mehrens, 'Overview on current status of lithium-Ion batteries' (2007) Second International Renewable Energy Storage Conference 19 - 21 November 2007 Bonn/Germany.

Stephen Karekezi; Waeni Kithyoma, 'Renewable energy development' (2003) The Workshop for African Energy Experts on Operationalizing the NEPAD Energy Initiative.

Shahidur R. Khandker; Hussain A. Samad; Rubaba Ali; Douglas F. Barnes 'Who Benefits Most From Rural Electrification? Evidence in India' (2012) Policy Research Working Paper 6095.

Teuku M. I. Mahlia; Tengku J. Saktisahdan; A. Jannifar; Masjuki H. Hasan; Hendrik S. C. Matseelar, 'A review of available methods and development on energy storage; technology update' (2014) Vol. 33 Renewable and Sustainable Energy Reviews 532-545.

Fabio Monforti-Ferrario, 'Renewable energies in Africa – current knowledge' (2011) JRC Scientific and Technical Reports.

'Off-grid & Microgrids' (Aquion Energy website) <http://www.aquionenergy.com/microgrid-energy-storage> accessed 26 November 2014.

Daniel H. Po Kang; Mengjun Chen; Oladele A. Ogunseitan, 'Potential Environmental and Human Health Impacts of Rechargeable Lithium Batteries in Electronic Waste' (2013) Vol. 47 No. 10 Environmental Science and Technology 5495–5503.

Paula Rolffs; Rob Byrne; David Ockwell, 'Financing Sustainable Energy for All: Pay-as-you-go vs. traditional solar finance approaches in Kenya' (2014) STEPS Working Paper 59 STEPS Centre.

SE4ALL Africa Hub Leaflet (on SE4All website) < http://www.se4all.org/wp-content/uploads/2013/10/SE4ALL-africa-hub-leaflet-web_Feb-2014.pdf> accessed 16 October 2014.

Nic Sharpley, 'Unlocking the potential of wind power with energy storage' (Wind power engineering & development website) <http://www.windpowerengineering.com/design/unlocking-potential-wind-power-energy-storage/> accessed 28 August 2014.

Gill Willkins, *Technology transfer for renewable energy. Overcoming barriers in developing countries* (Earthscan Publications Ltd 2002).

World Bank, 'Empowerment and Poverty Reduction: a Sourcebook' (2002).

Annabel Yadoo; Heather Cruickshank, 'The value of cooperatives in rural electrification' (2010) Vol. 38 Energy Policy 2941-2947.