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Sustainable energy storage for solar home systems in rural Sub-Saharan Africa – A comparative examination of lifecycle aspects of battery technologies for circular economy, with emphasis on the South African context

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ABSTRACT

Photovoltaics (PV) are increasingly important for electrification in rural Sub-Saharan Africa, but what is the best battery technology to use? To explore this question, a small-scale domestic PV system for South Africa (20-year lifetime) to deliver 1.42 kWh electricity from batteries overnight with 10-h discharge was costed with various Li-ion, Pb-acid and Aquion aqueous hybrid ion batteries (AHIBs). Environmental impact; compatibility with circular economy; potential for cost-reduction through lifetime extension; and valorisation of batteries at end-of-life is discussed. Batteries are 81–93% of system costs, and battery production required over the system lifetime would emit 743, 674 and 6060 kg CO2-eq (Pb-acid, Li-ion and AHIBs respectively). Hazardous materials in Li-ion and Pb-acid batteries pose risks at end-of-life. Li-ion and AHIBs face potential resource supply constraints due to use of Co, Li and graphite. Closed-loop recycling and refurbishment of Pb-acid batteries is well established in South Africa. Currently, no African facilities for Li-ion or AHIB recycling exist, with little opportunity to retain material value from these batteries within the region. Despite lower efficiencies and shorter lifetimes, Pb-acid batteries, which are readily available from domestic manufacturing at low cost, are the current best choice for sustainable small-scale domestic PV systems in South Africa.

1. Introduction

Sub Saharan Africa (SSA) comprises 49 countries and covers an area of 24.3 million km [1]. This vast region accounts for >15% of the earth's land surface. As of 2015, the population of SSA was ~949,175,000 [2]. African countries are among the fastest growing in the world: the UN predicts 1.3 billion people will be added to the population by 2050 [1]. Decreasing infant mortality rates and increasing fertility rates have resulted in a high population under the age of 24, and by 2035 the number of working aged (18–64) Africans is expected to exceed the rest of the world combined [3]. Only ~37% of the population of SSA live in urban areas (≥90,000 inhabitants), with a very high percentage living in rural communities. SSA has the world's highest rate of urbanisation – 4%, [3] and by 2050, the UN projects that approximately 55% of the population will be in urban areas. Even so, this will leave a billion people or so in rural communities [1]. Population growth is putting more pressure on the land to supply food and fuel for energy. >80% of SSA still relies on wood for fuel without infrastructure in place for reliable supply of energy from alternative sources. As a result,

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Abbreviations: AHIB, aqueous hybrid ion batteries; CRMs, critical raw materials; DoD, depth of discharge; GWP, global warming potential; LIBs, Li-ion batteries; LFYP, lithium-iron-yttrium-phosphate batteries; PV, photovoltaic; SSA, Sub Saharan Africa; VRLA, valve regulated Pb-acid batteries.

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deforestation and subsequent land degradation rates will continue to rise [3].

Only 30% of the population of SSA had regular access to electricity in 2014, and although this number is rising [4] (Fig. 1), in many areas the rate of electrification is lower than population growth [5,6]. Political instability, poorly maintained and inadequate infrastructure, as well as unaffordable tariffs are major barriers to widespread electricity access. Access to electricity in rural areas is very low; in Angola and Chad, less than 5% of the rural population have access to electricity, and the International Energy Agency projects that despite major improvements to electrification across SSA, more than 500 million people living in rural areas will still be without electricity in 2040 [4].

As of 2014, electricity in SSA was provided mainly from coal (45%), hydropower (22%), oil (17%), gas (14%) [4]. Nuclear accounts for just 2% and renewables such as wind and solar photovoltaics (PV) account for <1% [4]. Diesel-powered generators are frequently used to supplement unreliable electricity supplies in both homes and businesses and account for approximately 3% of energy usage throughout SSA [3,4]. Widespread use of diesel generators results in impacts on human health and climate change due to particulates and NO_x emissions [5]. The cost of electricity from diesel generators is double that from solar microgrids [6].

The need for wider deployment of renewable energy systems for electrification and supply of affordable electricity (Fig. 1) [3], as well as sustainable economic development and initiation of new industry to provide opportunities for employment for the ever-growing population of SSA is urgent [4].

The high number of sunny hours each season make solar energy an obvious choice to explore for the area (Fig. 2) [7,8], and it is a particularly attractive option for North-eastern and Southern Africa, where annual solar radiation ranges from 2400 to 2800 kWh/m^2 [3,4,9]. African governments have set ambitious targets for PV installation. Nigeria aims to install 30,000 MW of PV by 2030, most of this as off-grid systems. Ghana aims to install 30,000 solar home systems by 2020 and invest $230 million into solar energy projects, including mini-grids and stand-alone solar PV systems. Other countries have similarly ambitious targets. The Africa Renewable Energy Initiative has a 30 GW target for installed capacity, and solar PV will be a major component of this [10].

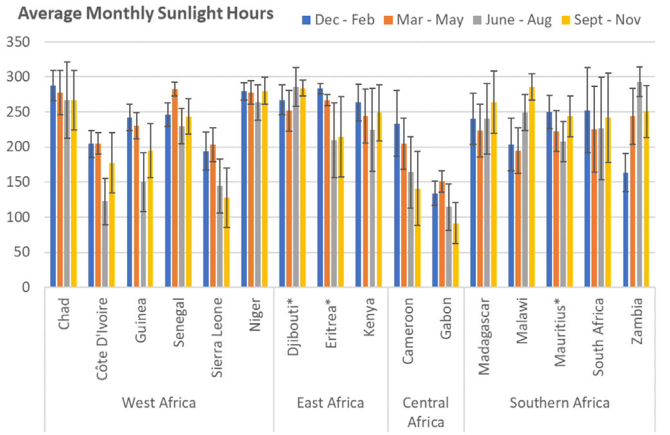


Fig. 2. Seasonal average hours of sunlight across Sub Saharan Africa [8] (* indicates a country with less than 3 monitoring stations available).

Although viewed as 'green' energy technologies, PV systems deployed into Africa have environmental impacts associated with manufacture, and during end-of-life when components cease to be of use and become waste electrical and electronic equipment (WEEE, or e-waste) [11]. As is true of much WEEE, improper management at end-of-life will result in detrimental impacts to human health and the environment due to the presence of hazardous materials [12]. In addition, the generation of WEEE can result in depletion of finite 'critical raw materials' (CRMs) [13]. Despite these issues, the large volumes of WEEE which will be generated following deployment of solar energy systems in Africa also presents significant opportunities in terms of sustainable economic development for SSA if these products and their constituent materials can be retained within a 'circular economy'. The question this paper aims to address is - what is the most suitable battery technology for sustainable solar energy storage for small scale domestic use in rural Africa within such a circular economy?

Fig. 3 shows the essential features of the circular economy, an alternative to current 'take-make-use-dispose' linear economic models. Retention of materials within the economy through recovery and regeneration of products at the end of each service life maximises their economic productivity, offsetting demand for primary resources and decoupling growth from resource consumption. Circular economy is regenerative by design and replaces the concepts of 'end-of-life' and 'waste' with 'restoration' and 'resources'. Key features include elimination of waste through industrial symbiosis, superior product design, appropriate business models and reverse logistics systems [14].

Adoption of circular economy with efficient collection systems

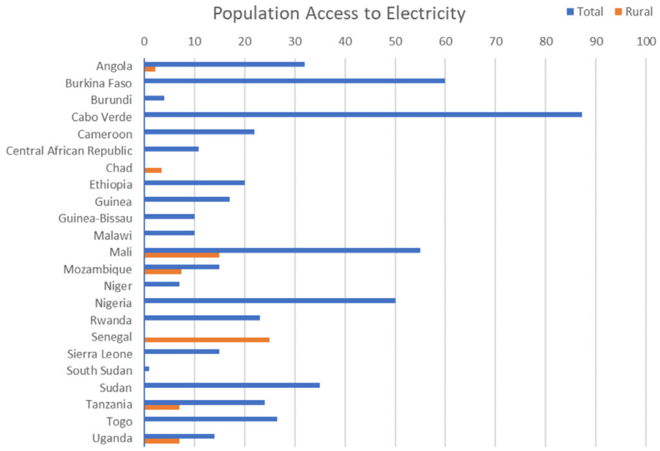


Fig. 1. Percentage of population in Sub-Saharan Africa with regular access to electricity [3].

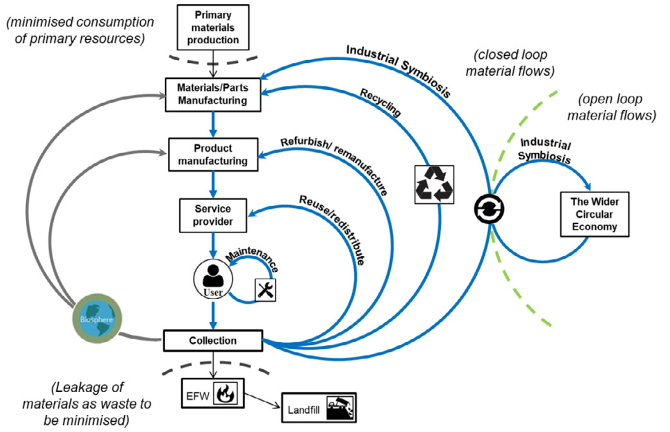


Fig. 3. Material flows within the circular economy (adapted from Ellen MacArthur Foundation [12]).

for end-of-life products and prioritising reuse and repair > refurbishment/upgrade > remanufacturing > recycling within SSA will mitigate potential environmental impacts of WEEE from PV systems, and create employment opportunities through the establishment of new industry for these processes [15]. The economic benefits of a circular economy are expected to become increasingly important into the future as the costs of primary raw materials, and safe disposal, rise [16]. In addition, a circular economy model will offset demand for primary raw materials for new PV system components, and reduce emissions from manufacture [11]. Appropriate collection and end-of-life treatment will also prevent detrimental impacts on human health and the environment resulting from hazardous materials contained in PV WEEE, or generated through 'backyard' recycling operations.

Currently four main battery technologies dominate stationary energy storage applications (Table 1) [17]. Lithium ion (Li-ion) batteries represent the majority of installed storage capacity and are commonly used in domestic PV systems. Of the four types of battery detailed in Table 1, vanadium redox flow batteries (VRFB) require pumps for electrolyte flow and additional energy and storage capacity to support this. This along with the additional mechanical complexity of VRFB systems makes them unsuitable for the small-scale domestic application discussed here. High temperature NaNiCl batteries (Table 1) are unsuitable because of the hazards associated with molten metal electrodes. For these reasons, this paper will focus on LIBs, VRLA and AHIB batteries.

In Swansea University, the SPECIFIC Innovation and Knowledge Centre (www.specific.eu.com) team has constructed a pair of buildings to demonstrate 'buildings as power stations' using technologies embedded into building envelopes to generate, store, and release energy. Li-ion batteries (LIBs) have been used for energy storage in the 'Active Office' – the UK's first energy positive office space, situated on Swansea University's Bay Campus [18]. This has roof integrated CIGS PV, combined solar thermal/PV generating technology integrated into the south facing wall and air source heat pumps for energy generation coupled with 110 kWh of Li-ion batteries and a 2000 L thermal store (93 kWh at 85-45 °C) to time shift heating and electricity demand. The second of these buildings, the ~200 m^2 'Active Classroom' has a 17 kWp roof integrated CIGS PV installation, transpired solar air collectors integrated into the external south wall for heating, and 60 kWh capacity Aquion aqueous hybrid ion batteries (AHIB) (C2C certified) for clean and safe energy storage [19,20]. No lead-acid batteries were used in either of these installations. By way of contrast, over recent years there have been a number of analyses of environmental performance of grid independent PV and/or hybrid systems for rural environments in general, [21] and with specific discussion of systems for: Algeria, [22] Ghana, [23] Nigeria, [24,25] and Venezuela, [26] and in all of these cases lead-acid batteries were used for electricity storage. Furthermore, in our own work in Africa, a team from Swansea University installed a small scale off-grid solar energy structure with 1.4 kWp of integrated PV in an orphanage in Mutende, Lulamba, Zambia (Fig. 4), [27] using two 12 V, 102 Ah lead-acid batteries. They seemed an obvious choice given they are the lowest cost option, readily available at the required capacity, easily replaced, durable, and provided the required capacity. But is lead-acid the best choice of battery technology for rural Africa from a sustainability and circular economy perspective?

Table 1
Globally installed stationary energy storage capacity by battery type [17].

Battery Technology	Installed Capacity	
	MW	*GWh*
Li-ion	~1300	1.27
Hight temperature NaNiCl	171	1.01
Valve regulated Pb-acid (VRLA)	196	0.173
Vanadium Redox-flow batteries (VRFB)	114	412

Determining the best battery choice for off-grid rural PV applications within the context of circular economy is non-trivial, depending on many geographically specific factors such as: weather; availability of infrastructure; skills for proper operation and maintenance; and end-of-life management via reuse, remanufacturing and recycling. For this reason, this paper considers the South Africa context, the region of SSA with which the authors are most familiar. However, the purpose is not to propose South Africa as a model solution for SSA, but, in part, to emphasise the importance of considering specific local conditions in identifying sustainable PV solutions for SSA, using South Africa as an example.

2. Method

To evaluate the suitability of commercially available LIBs, VRLAs and AHIB for application in PV systems for rural South Africa, a suitable PV system for rural South Africa was specified, and an evaluation of the system costs over its 20-year target lifetime was made. This was conducted for 8 systems containing different currently available batteries: 4 lithium-iron-yttrium-phosphate (LFYP), 3 VRLA, 1 AHIB. Lifetime costs are compared with the value of electricity generated to identify the best batteries in terms of techno-economic performance. Recommendations of how system costs may be reduced and off-set through circular economy practices are made. Finally, evaluations of potential hazards and emissions from the lifecycles of batteries, resource efficiency implications and existing infrastructure to support circular economy for the three battery technologies were conducted. Battery technology is developing rapidly and so evaluation here focuses on PV system components and batteries which could be purchased in South Africa and put in place immediately, with emphasis on those commercially available within South Africa.

2.1. Defining the system

To establish the specification of the system, the energy requirements of households to be met must first be defined. South African energy suppliers introduced a scheme to provide 50 kWh/month 'free basic electricity' to grid-connected households, with a plan to develop off-grid solar powered systems providing 50 kWh/month to rural households [28]. 50 kWh/month is ~1.67 kWh/day, significantly lower than the average daily consumption of ~8 kWh/

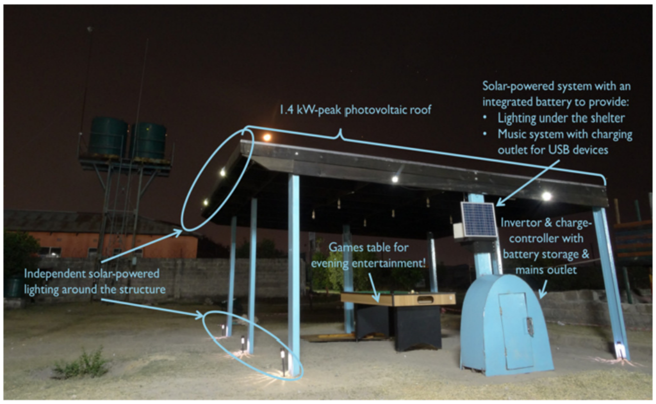


Fig. 4. Off-grid solar energy structure with 1.4 kWp of integrated PV and 2.45 kWh of VRLA batteries in an orphanage in Mutende, Lulamba, Zambia.

day by grid connected homes in South Africa, but sufficient for basic commodities such as lighting, TV, radio, cell phone charging, washing, and possibly refrigeration (Table 2). If 85% of this energy was required overnight, then ~1.42 kWh of energy must be supplied from battery storage.

Operational conditions have a strong influence on battery performance and lifetime, and South Africa is a tough environment in terms of wide variation in, and often high, ambient temperatures. To mitigate this, it is proposed that batteries be buried at a depth of ~1.5 m where the insulation and thermal lag due to soil cover, is expected to limit temperature variations to ~12–25 °C, thereby maximising battery life [29]. It is proposed batteries be buried within a waterproof box, and ventilated with a capped chimney to the surface to enable air to circulate and prevent water from entering.

Batteries are oversized to ensure suitable depth-of-discharge (DoD) to obtain sufficient cycle lives and compensate for reducing storage capacity and discharge over time (typically 5–15%/month for VRLA, and <2% per month for LFYP). The need for oversizing varies with battery chemistry and its tolerance to deep discharge. DC-DC round-trip efficiency also varies with battery chemistry. For this reason, PV must also be oversized to deliver the required 1.42 kWh of energy overnight from storage. System PV and battery requirements were calculated using literature data [17].

The standard crystalline silicon (c-Si) PV module size required to generate the required energy, was calculated using the NREL PVWatts Calculator [30], using weather data for Johannesburg, RSA. 15% module efficiency, fixed roof mounting with a tilt angle of 33° and Azimuth of 0°, and default value of 14.08% system losses (accounting for standard efficiency losses in the system as a result of soiling, shading, resistive losses in connections etc.), were specified. Average daily electricity generation by month was calculated to verify sufficient energy would be produced by the system to meet specified demand even at times of lowest solar irradiance.

Rate of discharge affects the usable capacity of batteries, with faster discharge times reducing capacity, and for this reason, usable capacities at a 10-h discharge rate obtained from manufacturer data sheets from retailer websites [31,32] were used in calculations.

2.2. Costing the system

The costs of PV panels, fixings, cables, connectors, charge controller and fuses are costed based on prices of commercially available components within South Africa. Battery costs for each of the 8 proposed systems include subsequent costs of purchasing replacement batteries over the 20-year lifetime of the system. The cost of energy storage for each battery set is also calculated in €/kWh for comparison. The number of replacements is calculated from previously identified lifetimes at specified DoD for each system. All costs of system components and batteries are those obtained from sustainable.co.za on 6/12/17,[31] except for AHIBs, which must be imported, and for which a UK commercial price obtained on the same date is used [32]. Prices are converted to Euros (€) from South African Rand (R) using an exchange rate of 16.03 R/€. The total lifetime cost of the system is then presented with the proportion of overall costs represented by each of the system components. Maintenance and waste management costs are not included in lifetime costs of the systems due to a lack of accurate data for the region. A comparison of potential EoL costs for each battery technology is made in subsequent sections based upon assessment of available infrastructure for EoL management.

2.3. Cost-benefit of system

The lifetime costs of each system are compared to the value of electricity generated over the system lifetime using 1.39 R/kWh (0.096 €/kWh), as a typical cost for electricity in Durban (private communication, Prof. Bice S. Martincigh, School of Chemistry & Physics, University of KwaZulu-Natal, Durban, RSA). This enables the most economic battery systems to be identified. Remaining capacity of these battery systems at the end of their specified lifetimes (i.e. when capacity reaches 80% of original capacity) is calculated and informs an examination of potential strategies for enhancing the overall cost-benefit of the system through extension of battery lifetime.

2.4. Carbon footprint and lifecycle impact considerations

A comparison of global warming potential (GWP) from production of the batteries for the four least expensive systems has been made using data given in Table 3. GWP for each installed battery ($\boldsymbol{GWP_{battery}}$) is calculated by equation (1), where $\boldsymbol{C}$ is the nominal capacity of installed batteries in kWh units. The total GWP of all batteries initially installed in the system ($\boldsymbol{GWP_{installed}}$) is given by equation (2), where $\boldsymbol{n_{bat}}$ is the number of batteries initially installed in the system. The total GWP associated with production of all batteries required over the system lifetime ($\boldsymbol{GWP_{total}}$) is given by equation (3), where $\boldsymbol{n_{replacements}}$ is the number of times batteries require replacement over the lifetime of the system.

$$GWP_{battery} = CF_{prod} \times C \tag{1}$$

$$GWP_{installed} = GWP_{bat} \times n_{bat} \tag{2}$$

$$GWP_{total} = GWP_{installed} \times \left(n_{replacements} + 1\right) \tag{3}$$

An evaluation was then conducted of other major impacts resulting from emissions in production of batteries and their raw materials, as well as additional hazards which could result from

Table 3
Carbon footprint of production data (CF_{prod}) for manufacturing VRLA, LFYP and AHIB batteries.

Battery Type	CF_{prod} (*kg CO_2-eq/kWh*)
VRLA	51.6[17]
LFYP	168.56[17]
AHIB	1,000[33]

Table 2
Example daily energy consumption for DC domestic appliances.

Item	Usage	Energy consumption (*kWh/day*)
TV (32 inch LCD)	5 h	0.35
Small DC fridge (50 W)	24 h	1.2
Compact fluorescent light (one 14 W bulb)	5 h	0.07
Cell phone charger (5 W)	3 h	0.01
Washing machine (500 W)	1 h	0.5
Total Energy Consumption		**2.13**

improper management of batteries both in use and at end-of-life.

2.5. Resource efficiency and circular economy considerations

To assess the potential global resource criticality implications and potential limitations to deployment of technologies resulting from resource security issues, component materials of various LIB chemistries, Pb-acid and AHIB batteries are considered against the British Geological Society Supply Risk Index [34] and those which have been found to be CRMs in recent assessments are highlighted. Finally an assessment of prospects for collection and EoL treatment of waste batteries in the region is made, along with an examination of industries which enable refurbishment, reuse, or may provide a pathway for closed-loop valorisation of recovered materials in manufacturing new batteries.

3. Results and discussion

In this section we consider the most economical of the battery systems examining the total cost contribution of batteries over the lifetime of the proposed PV system. An assessment of the environmental impacts associated with production of batteries and potential impacts resulting at end-of-life in the absence of proper waste management systems are also considered along with resource security and critical raw materials issues associated with each of the battery technologies. Finally, existing infrastructure within South Africa to support a domestic circular economy around batteries is reviewed, with recommendations made as to which batteries are most likely to become the basis of viable circular economy in the region.

3.1. Defining the system - battery storage and PV requirements

Table 4 indicates the calculated battery capacity required for the PV system depending on battery chemistry and depth of discharge used, along with the required energy generation from PV when battery efficiencies are taken into account. VRLA batteries are used with much lower depth of discharge than Li-ion batteries in order to achieve suitable lifetimes, and so considerable additional oversizing is required for VRLA in comparison to Li-ion and AHIB batteries. The lower efficiency of VRLA requires greater PV generation than LIBs if the same amount of electricity is to be available from storage following losses during battery charging.

LFYP batteries have the highest efficiencies at 96%, followed by AHIB at 83% and VRLA at 76.5%. Efficiency losses are greatest for VRLA and so systems using these batteries requires greatest oversizing.

The calculated annual, average monthly and daily electricity output of 500 Wp of c-Si PV is given in Table 5. This would generate 869 kWh of electricity per year, with a minimum monthly generation of 62 kWh in February.

3.2. System costs

Table 6 shows a breakdown of system component costs excluding batteries, which totals ~€560. The charge controller is the most expensive of these components, followed by the two 250 Wp c-Si PV modules.

Table 7 compares costs and characteristics of the battery systems. The capacity of each given a 10-h discharge rate, and number of batteries required for initial installation in each system and over its 20-year life is indicated. On average, commercially available VRLA batteries are significantly cheaper than LIB or AHIB batteries per kWh of storage capacity (~7 and ~3 times respectively). The easy availability and low capital investment costs of Pb-acid batteries are very attractive, but Pb-acid gives low cycle-lives in comparison to LIBs and AHIB, and also has high sensitivity to deep discharge. Significant oversizing of capacity is therefore required in comparison to other technologies, and the relatively short lifetimes for Pb-acid batteries mean that these must be replaced more regularly (3–5 times compared to once for Li-ion and twice for AHIB) over the lifetime of the proposed system.

Fig. 5 compares the lifetime costs of each system with the value of electricity generated by the system. Batteries represent the major part of total system costs, at 81% and 93% of the costs in the least and most expensive systems costed respectively. VRLA batteries represent the lowest initial capital investment. This is the case for all VRLA systems costed (shown in dark blue) and is important when initial cost is a barrier to system installation. System **1** is the

Table 5
Annual DC electricity output of 500 Wp c-Si PV array with 15% efficiency in Johannesburg, RSA.

Month	DC array Output (kWh)	Daily output (kWh)
Jan	68.7	2.22
Feb	62.7	2.16
Mar	73.0	2.35
Apr	71.6	2.39
May	75.9	2.45
Jun	73.5	2.45
Jul	78.7	2.54
Aug	81.5	2.63
Sep	75.3	2.51
Oct	75.2	2.43
Nov	68.3	2.28
Dec	71.6	2.31
Total	876	

Table 4
Required PV electricity generation and battery capacity to supply 1.42 kWh of DC electricity from storage, based on typical voltages and efficiencies at typical maximum DoD values for VRLA, LFYP and AHIB batteries (DoD: depth of discharge; VRLA: valve regulated Pb-acid battery; LFYP: lithium iron yttrium phosphate battery; AHIB: Aquion hybrid ion battery).

Battery type	Nominal voltage	Efficiency (DC-DC) [16]	Total required daily PV electricity generation (*Wh*)	Typical max DoD	Approximate required battery capacity (*Ah*)
VRLA	12 V	76.5%	2102	50%	236
				30%	394
				15%	787
LFYP	13 V	96%	1726	100%	109
				80%	136
				70%	156
LFYP	24 V	96%	1726	100%	54
				80%	68
				70%	78
AHIB	48 V	83%	1957	80%	37
				70%	42

Table 6
Costs of PV system components available in South Africa without batteries (prices used for components are those from sustainable.co.za on 6/12/17,23 exchange rate = 16.03 R/€).

Component	No.	Item	Cost (€)
Charge controller	1	Microcare 20 Amp LED MPPT Charge Controller	127.84
PV	2	Renewsys Deserv 250 W Solar Panel	274.29
Roof mounting system	1	Sustainable 2 Panel Solar Mounting Kit	65.35
Fuse and holder	1	Sustainable: 200 Amp TF Fuse and 200 Amp CSM Holder	61.63
Cables	1	Sustainable 250 mm Black Battery Connector Pack of 4	10.66
	1	Sustainable 6 mm [2] Black Double Insulated Halogen Free Solar Cable	1.05
	1	Sustainable 6 mm [2] Red Double Insulated Halogen Free Solar Cable	1.05
	1	Sustainable 6 mm [2] Black Panelflex 5 m	3.72
	1	Sustainable 6 mm [2] Red Panelflex 5 m	3.72
	1	Sustainable 10 mm^2 Red Panelflex	1.83
	1	Sustainable 10 mm^2 Black Panelflex	1.83
	1	Sustainable 2.5 mm^2 Earth Panelflex (15 m)	4.65
Connectors	20	Sustainable 6mm^2/10 mm Lugs	0.31
	20	Sustainable 10mm^2/10 mm Lugs	0.37
Total			**558.31**

Table 7
Details of suitable batteries for six potential off-grid PV systems and the depth-of discharge (DoD) achieved for each based upon overnight discharge of 1.42 kWh, all batteries are commercially available within South Africa from sustainable.co.za except [31] AHIB for which data is obtained from windandsun.co.uk [32] (battery specifications taken directly from manufacturer data sheets available from retailers).

#	Type	Battery	Nominal voltage	Lifetime (yrs)	Unit price (€)	Capacity at 10 h discharge (Ah)	No. batteries		DoD	Total storage (kWh)	Cost of storage (€/kWh)
							Initially installed	Over system lifetime			
1	VRLA	Trojan T-1275	12	5.0 @50%DoD	290	268	2	8	44%	3.22	180
2	VRLA	CB Solar DC12-260 12 V 260 Ah	12	3.8 @30%DoD 4.7 @15%DoD	477	520	2	12	23%	6.24	153
3	VRLA	SonX RA12 150 Ah 12 V	12	3.8 @30%DoD 4.7 @15%DoD	241	450	3	18	26%	5.40	134
4	LFYP	Blue Nova BN13V-154-2 k mini	13	9.9 @100%DoD 13.7 @80%DoD 19.2 @70%DoD	1775	154	1	2	71%	2.00	887
5	LFYP	BlueNova BN13V-77-1.0 k Micro	13	9.9 @100%DoD 13.7 @80%DoD 19.2 @70%DoD	1550	154	2	4	71%	2.00	1548
6	LFYP	BlueNova BN13V-310-4 k	13	9.9 @100%DoD 13.7 @80%DoD 19.2 @70%DoD	3779	308	1	2	35%	4.00	944
7	LFYP	BlueNova BN26V-77-2 k Mini	26	9.9 @100%DoD 13.7 @80%DoD 19.2 @70%DoD	1775	77	1	2	71%	2.00	886
8	AHIB	Aquion S30-0080 Battery stack	48	11.0 @70%DoD	1067[a]	42	1	3	70%	2.02	504

[a] Calculated from price in UK at rate of 1.14 €/£

lowest cost, requiring an initial outlay of €1139 compared with €1575 for the AHIB system (**8** shown in light blue) and €2333 for the least expensive Li-ion systems (13 V **4** shown in green and 26 V **7** shown in red). The lower cost of Trojan T-1275 VRLA batteries and relatively few replacements over the system lifetime compared to other VRLA batteries costed result in lowest lifetime costs for system **1**. However, significant oversizing and more frequent replacement of batteries result in higher lifetime costs of the other Pb-acid systems (**2** and **3**), higher than for the AHIB system (**8**) which is second cheapest overall, followed by Li-ion systems **4** and **7** which require fewer battery replacements and less oversizing. Both the 13 V Blue Nova BN13V-154-2 k mini LFYP battery (**4**) and 26 V Blue Nova BN13V-26V-77-2 k-mini battery (**7**) result in similar costs of €1775 each, however it is possible that additional savings with the 26 V system may be achievable by discharging lower current at higher voltage avoiding the necessity of cabling with the same gauge as the 13 V system. Discharging at lower current may also enable greater efficiencies and useable storage capacity in systems with higher voltage. This could result in lower DoD and therefore longer battery lives. Regardless of battery technology adopted, none of the costed systems come out as cost effective over 20 years; in all cases they cost more than the value of the electricity they produce.

To make the system cost-effective, reduction of lifecycle costs is necessary. From the system cost profiles, it is clear that extension of battery lives could reduce costs significantly. With the high number of VRLA battery replacements necessary, a small lifetime extension of each could avoid the necessity to install a whole set of batteries over the system lifetime. The LFYP batteries have lifetimes close to the 20-year lifetime of the system, only requiring replacement within the final year of the system life. A small extension to lifetimes of these high cost batteries would also result in considerable savings if replacement within the system lifetime could be avoided. It should be noted that typical failure thresholds for batteries are 80% i.e. at the stated lifetime of the battery, its capacity is 80% of that when it was new. This means that batteries are still functional at end-of-life, however deeper discharge will be required to continue to provide the same amount of energy. At 80% of initial battery capacity, the least expensive systems costed (**1**, **4**, **7** & **8**) will have capacities indicated in Table 8, requiring DoDs indicated to

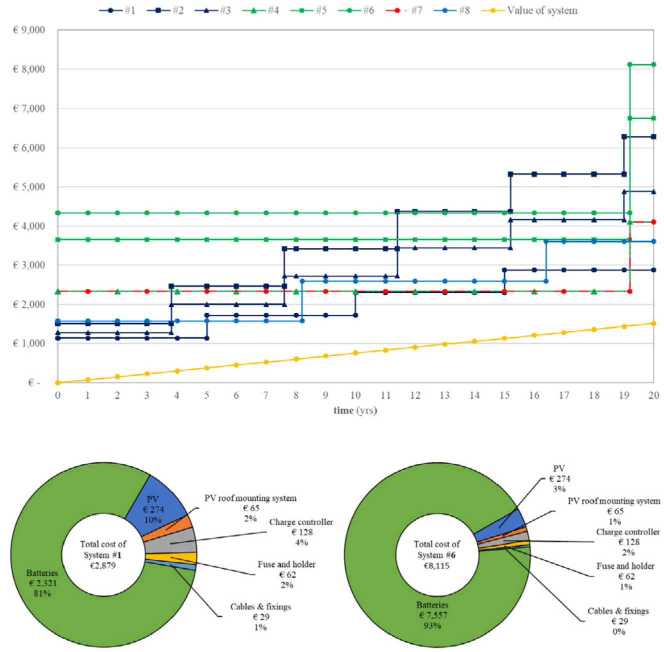


Fig. 5. Estimated costs of off-grid, DC PV systems in Durban over 20 year lifetimes compared with the value of generated electricity (top) with breakdown of costs of least expensive VRLA based system #1 (bottom left) and most costly LFYP based system #6 (bottom right); maintenance costs are excluded.

continue to meet overnight energy requirements. Given the oversizing specified for each of these systems, batteries can be used past their stated lifetimes. In the case of VRLA batteries for system **1**, DoD at the end of the specified lifetime is 55%, close to the recommended max DoD of 50%. Although Pb-acid batteries are sensitive to deeper discharge and likely to degrade quickly after this point, longer use than the specified lifetime would be possible given the extent of oversizing in this case. The same is true for the LFYP batteries of systems **4** & **7**, and the AHIB for system **8**. LFYP batteries have stated max DoDs of 100% and so it may be possible to avoid their replacement over the system lifetime altogether. Furthermore, the use of a ‘circular economy’ approach can give cost savings by: utilising remanufactured, refurbished or repurposed batteries or batteries manufactured from recovered materials; and valorising end-of-life batteries to recoup costs by diverting them to reuse, remanufacturing and recycling processes.

3.3. Carbon footprint and lifecycle impact consideration

Fig. 6 compares the carbon footprints of production (CF-prod) attributable to manufacturing single batteries for the systems, all initially installed batteries, and all batteries required over the lifetime of the system from the data presented in Table 9 *using **equations 1–3***. The GWP of the AHIB for system **8** is by far the highest. The 3 batteries required over the lifetime of the system result in >6000 kg CO_2-eq, with production of just a single AHIB exceeding that of all VRLA batteries over the lifetime of system **1** and the all LFYP batteries required over the lifetimes of systems **4** and **7** by an order of magnitude. The high GWP of AHIB batteries is dominated by the use of tetrafluoroethylene (TFE) which is used as the binder in the electrodes of these cells [33]. These fluorinated hydrocarbons are strong greenhouse gases, and leakage of small amounts during production results in considerable impact to the GWP of AHIB batteries. The individual LFYP batteries used in systems **4** and **7** have a GWP ~4 times higher than that of the Pb-acid batteries used in system **1.** However, due to the requirements to install 2 batteries in system **1** to achieve required overcapacity, and the need to replace these batteries four times over the lifetime of the system, overall the use of VRLA batteries in system **1** results in greater GWP than the use of LFYP batteries in systems **4** and **7** (743 vs. 674 kg CO_2-eq). While Pb-acid batteries are the cheapest option by a significant margin, their use results in greater global warming potential over the 20-year lifetime of the system than Li-ion alternatives.

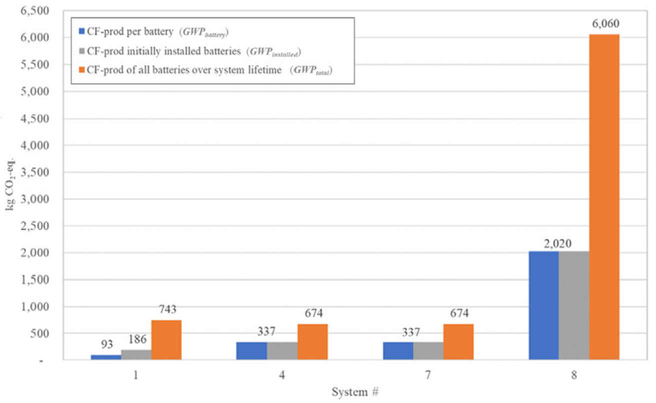


Fig. 6. Carbon footprints of batteries for the system (based on data from Baumann et al. [17] and Peters and Weil [33]).

Carbon footprint of batteries production is useful for a comparison of GWP, but gives only a limited picture of the environmental impacts of batteries. Further consideration of emissions during production highlights that production of Li-ion batteries from primary raw materials results in considerable SO_2 emissions and water contamination. Consideration of the hazardous nature of materials within batteries and their potential impacts if not properly managed is also important. Issues relating to end-of-life of LIBs arise from: Co in cathodes; fluorine, arsenic and sulfonated compounds in electrolytes; and the extremely reactive alkali metal – Li. Improper treatment of VRLA batteries at end-of-life results in the release of Pb and sulfuric acid to the environment. These materials can directly impact human health through direct contact and through contamination of water and soil, and can accumulation in food chains when batteries are landfilled or recycled improperly [35]. This is of particular concern for rural SSA where batteries are installed in isolated underdeveloped areas which makes efficient collection difficult and costly.

The issue of hazardous waste arising from increased

Table 8
Battery capacity at 80% of initial capacity and depth of discharge (DoD) required to meet overnight energy requirements.

System	80% battery capacity (*Ah*)	Daily DoD to supply required energy	Change in DoD vs initially installed capacity
1	214.4	55%	+11%
4	123.2	88%	+18%
7	61.54	89%	+18%
8	33.60	88%	+18%

Table 9
Nominal battery storage capacities of batteries for most cost-effective systems with number of batteries initially installed for each system (n_{batt}) and number of battery replacements over the system lifetime ($n_{replacements}$).

System#	Battery	Type	Nominal capacity (*C*) (*kWh*)	n_{batt}	$n_{replacements}$
1	Trojan T-1275	VRLA	1.61	2	3
4	Blue Nova BN13V-154-2 k mini	LFYP	2.0	1	1
7	BlueNova BN26V-77-2 k Mini	LFYP	2.0	1	1
8	Aquion S30-0080 Battery stack	AHIB	2.02	1	1

deployment of batteries for solar home systems in Africa is significant. In 2016, 1.232 million tonnes of Pb-acid batteries were shipped to Africa containing >800,000 tonnes of Pb (equivalent to 10% of global production) [36]. The African Renewable Energy Initiative that was launched in 2015 has a 300 GW target for 2030, and solar will form a major part of installed capacity. Nigeria alone has a target of 30 GW of installed solar capacity, which will require an initial installation of over 40 million batteries, and if Pb-acid batteries are used to support the systems, 280 million batteries will have to be installed, recovered and recycled over the lifetime of these systems [9]. Furthermore, those recycling facilities that are licensed face serious competition from the informal sector which lack basic health and safety and environmental controls with lead poisoning of workers common, and fatal in some cases [36]. The informal sector formerly consisted of small scale backyard recycling operations, but these are now increasingly replaced by industrial scale smelters [37].

From a hazardous material point of view, AHIBs, which uses a manganese oxide cathode and alkali ion salt water electrolyte, are safest.

3.4. *Resource-efficiency and circular economy considerations*

3.4.1. *Critical materials*

CRMs used in batteries are shown in Table 10 with their current supply risk index from the British Geological Survey. Li-ion batteries face resource security issues due to Li, Co and graphite, as do Aquion cells which contain graphite. In the interests of global resource security, it is questionable whether technologies containing CRMs should be utilised without further consideration of available infrastructure to support collection and closed-loop recycling, refurbishment and remanufacturing. Pb-acid batteries contain no CRMs.

3.4.2. *End-of-life prospects & compatibility with circular economy*

Closed-loop recycling of VRLA batteries is well established in South Africa. First National Batteries operate a network of collection points across South Africa, which divert VRLA batteries to their smelting facility in Benoni for recycling. Recovered Pb and plastics are used to manufacture new batteries with optimised design for disassembly [39]. This suggests end-of-life costs will be low in comparison to other batteries which cannot be recycled domestically. Materials cost savings resulting from use of recovered components/materials should rise with volumes of VRLA batteries recycled in the future, and business models to maximise return of batteries at end-of-life such as ‘lease and takeback’ schemes or deposit schemes, may improve recycling rates. Several businesses within South Africa operate a Pb-acid battery reconditioning service which reverses the sulfation process that limits their working life. This presents opportunities to extend the longevity of VRLA batteries and reduce battery replacement costs over the system lifetime.

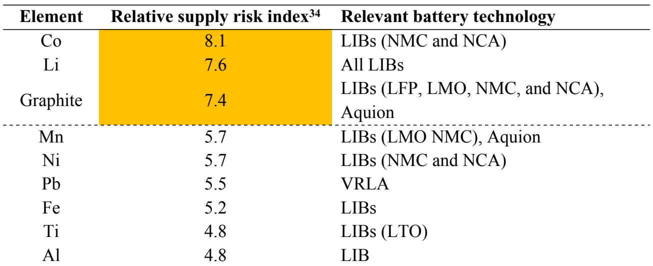
No LIB recycling exists in Africa [40]. Li-ion batteries are collected and shipped to Europe for recycling, at considerable economic and environmental cost. This indicates LIB end-of-life costs in South Africa will be comparatively high with little of the social and economic value inherent in LIBs exploited within South Africa. High end-of-life costs increase the likelihood of improper end-of-life management with resulting impacts on populations and the environment. However, the South African government has funded research seeking to develop domestic LIB recycling, [41] and South Africa also has a recently emerging LIB manufacturing company – BlueNova (Solguard (Pty) Ltd., est. July 2015) who manufacture the LFYP batteries costed in this paper [42]. Together these could provide the opportunity to valorise any recovered materials from LIBs in closed-loop material flows within South Africa [41]. It may also be possible to source used LIB automotive batteries for reuse in the proposed system [43].

As an emerging technology yet to be deployed in Africa, AHIB batteries have few prospects for end-of-life treatment within the continent in the near future.

4. Conclusion

The specific outcome from this preliminary examination is the identification of VRLA batteries as current best choice of battery for

Table 10
Supply risks of materials in batteries, those highlighted in orange have been identified as CRMs in recent assessments [13,38].



Element	Relative supply risk index[34]	Relevant battery technology
Co	8.1	LIBs (NMC and NCA)
Li	7.6	All LIBs
Graphite	7.4	LIBs (LFP, LMO, NMC, and NCA), Aquion
Mn	5.7	LIBs (LMO NMC), Aquion
Ni	5.7	LIBs (NMC and NCA)
Pb	5.5	VRLA
Fe	5.2	LIBs
Ti	4.8	LIBs (LTO)
Al	4.8	LIB

Supply risk index runs from 1 (very low risk) to 10 (very high risk); LIBs – Li-ion batteries; LTO – lithium-iron-phosphate with lithium titanate anode; LFP- lithium-iron-phosphate with carbon anode; LMO- lithium-manganese-oxide; NCM– lithium-nickel-cobalt-manganese; NCA– lithium nickel-cobalt-aluminium-oxide; highlighted elements included in EU20 critical list [37].

sustainable small scale (50 kWh/month) domestic PV in South Africa, despite lower efficiencies and shorter lifetimes than Li-ion and Aquion batteries. This is justified by the ready availability of VRLA batteries in South Africa through domestic manufacturing; low cost; and existing infrastructure for refurbishment and closed-loop recycling. Despite relatively low costs, the proposed system is still not cost-effective over its 20-year lifetime, however adoption of circular economy practices holds great potential to improve this. Longevity of batteries is a key aspect to improving this, as is valorisation of batteries that reach end-of-life. Business models to maximise return of batteries at end-of-life such as 'lease and takeback' schemes or deposit schemes, may improve this.

Future developments for LIBs initiated by the South African government may in time enhance the benefits of LIBs for this application, however high initial costs for LIB systems, critical materials issues and poor prospects for refurbishment and remanufacturing cast doubt over the suitability of this technology for the proposed system.

Optimum battery use requires some knowledge of the technology, as does proper handling of waste batteries [35]. Thus, any system installation also requires: i) an additional basic education and training package on the benefits of solar energy, hazards associated with the technologies, and proper operation, maintenance and replacement of components; and ii) full system performance monitoring and analysis for problem/fault prediction/finding.

While this evaluation is made in the South Africa context, it is hoped that the framework for evaluation used will translate, leading to consideration of geographically specific circumstances when evaluating technologies for use in PV systems across SSA. In this way, optimum solutions to battery selection and end-of-life management can be developed to support sustainable off-grid PV systems, using the circular economy model, for social, environmental and economic benefits across Sub Saharan Africa.

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References

[1] UN. World population prospects: 2015 revision. United Nations, New York: Department of Economic and Social Affairs; 2015.
[2] UN. Population, consumption and the environment 2015. New York: Department of Economic and Social Affairs/Population Division, United Nations; 2015.
[3] Europa publications, frame I, Africa south of the Sahara 2017. 46th Ed. New York: Routledge; 2016.
[4] Birol F. Africa energy outlook. Paris, France: IEA; 2014.
[5] Knippertz P, Evans MJ, Field PR, Fink AH, Liousse C, Marsham JH. Nat Clim Change 2015;5:815–22.
[6] Akinyele DO, Rayudu RK. Energy 2016;109:160–79.
[7] Charles RG, Davies ML, Douglas P, Hallin IL. Chapter 5 – Sustainable solar energy collection and storage for rural Sub-Saharan Africa. In: Fthenakis VM, Letcher T, editors. A comprehensive guide to solar energy systems. Maryland Heights, MO, USA: Academic Press; 2018. pp81–107.
[8] Huld T, Müller R, Gambardella A. Sol Energy 2012;86:1803–15.
[9] WMO. UNdata: sunshine. Geneva, Switzerland: World Meteorological Organization; 2010.
[10] Schroeder P. Will solar PV create a wave of toxic battery waste in rural Africa? Institute of Development studies; 2016. http://www.ids.ac.uk/opinion/will-solar-pv-create-a-wave-of-toxic-battery-waste-in-rural-africa. [Accessed 22 September 2017].
[11] Charles RG, Davies ML, Douglas P. Third generation photovoltaics; Early intervention for circular economy and a sustainable future. 2016. p. 1–8. Electronics Goes Green 2016+ (EGG).
[12] Charles RG, Douglas P, Hallin IL, Matthews I, Liversage G. Waste Manag 2017;60:505–20.
[13] Charles RG, Douglas P, Baker JA, Carnie MJ, Douglas JO, Penney DJ, Watson TM. J Clean Prod 2018;202:1167–78.
[14] Ellen Macarthur. Foundation, Towards a circular economy - Economics and business rationale for an accelerated transition. Ellen MAcArthur Foundation; 2013. http://www.ellenmacarthurfoundation.org/business/reports. [Accessed 21 October 2017].
[15] Morgan J, Mitchell P. Employment and the circular economy. WRAP, Green Alliance; 2015. http://www.wrap.org.uk/sites/files/wrap/Employment%20and%20the%20circular%20economy%20summary.pdf. [Accessed 10 December 2017].
[16] Lacy P, Keeble J, McNamara R, Rutqvist J. Circular advantage: innovative business models and technologies to create value in a world without limits to growth. Accenture Strategy; 2014.
[17] Baumann M, Peters JF, Weil M, Grunwald A. Energy Technol 2017;5:1071–83.
[18] SPECIFIC, Active Office – the UK's first energy-positive office space. 2018. http://www.specific.eu.com/assets/downloads/casestudy/Active_Office_Case_Study.pdf. [Accessed 28 July 2018].
[19] SPECIFIC, active Classroom. 2016. http://www.specific.eu.com/assets/downloads/casestudy/Active_Classroom_Web_Case_Study.pdf. [Accessed 15 December 2017].
[20] blu.sky energy gmbh, Clean energy requires clean batteries, Aquion - the world's safest and cleanest energy storage for your home. 2014. http://www.bluesky-energy.eu/aquion-the-saltwater-battery/?gclid=CKmor_-O8tMCFe6_7QoduU4CRg. [Accessed 16 May 2017].
[21] Akinyele DO. Energy 2017;130:515–29.
[22] Rezzouk H, Mellit A. Renew Sustain Energy Rev 2015;43:1134–50.
[23] Adaramola MS, Agelin-Chaab M, Paul SS. Energy Convers Manag 2014;88:284–95.
[24] Akinyele DO, Rayudu RK. Energy 2016;109:160–79.
[25] Adaramola MS, Paul SS, Oyewola OM. Energy Sustain Dev 2014;19:72–82.
[26] López-González A, Domenech B, Ferrer-Martí L. Energy 2018;159:229–42.
[27] Swansea university, Zambia summer expeditions. 2017. http://www.swansea.ac.uk/engineering/zambia/. [Accessed 16 May 2017].
[28] Jamal N. J Energy South Afr 2015;26:58–65.
[29] Hillel D. Introduction to soil Physics. Academic Press Inc, Elsevier Inc; 1982.
[30] NREL. PVWatts calculator. 2017. http://pvwatts.nrel.gov/pvwatts.php. [Accessed 6 December 2017].
[31] Sustainable.co.za, Sustainable.co.za - SA's No. 1 Online Eco Store. 2017. https://www.sustainable.co.za/sustainable-10mm-6mm-lugs.html. [Accessed 6 December 2017].
[32] Wind, Sun Ltd. Aquion energy salt water batteries. 2017. http://www.windandsun.co.uk/products/Batteries/Aquion-Energy-Batteries#10918. [Accessed 8 December 2017].
[33] Peters JF, Weil M. J Power Sources 2017;364:258–65.
[34] British geological Survey, risk list 2015. 2015. https://www.bgs.ac.uk/mineralsuk/statistics/riskList.html (10/12/2017).
[35] Cesaro A, Marra A, Belgiorno V, Guida M. J Clean Prod 2017;142:2656–62.
[36] Manhart A, Amera T, Kuepouo G, Mathai D, Mng'anya S, Schleicher T. The deadly business – findings from the lead recycling Africa project. Öko-Institut e.V.; 2016.
[37] Factor. PV/battery waste management in the context of rural electrification support on pv/battery waste management for a rural electrification program. Clean energy Solutions Center, NREL; 2016.
[38] EC. Report on Critical Raw Materials for the EU - Report of the Ad hoc Working Group on Defining Critical Raw Materials. 2014.
[39] ESI Africa – Africa's power journal, recycling of batteries in South Africa. 2013. https://www.esi-africa.com/news/recycling-of-batteries-in-south-africa/. [Accessed 15 December 2017].
[40] Saloojee F, Lloyd J. Lithium battery recycling process - desktop study. CM Solutions Metallurgical Consultancy & Laboratories; 2015.
[41] Knights BJD, Saloojee F. Lithium battery recycling - keeping the future fully charged. Department of Environmental Affairs, Greenfund, Development Bank of South Africa; 2015.
[42] BlueNova. BLUE NOVA energy. 2017. https://bluenova.co.za/. [Accessed 15 December 2017].
[43] Ahmadi L, Young SB, Fowler M, Fraser RA, Achachlouei MA. Int J Life Cycle Assess 2017;22:111–24.