Access to Energy Storage

Insights from off-grid energy providers and market enablers

Preliminary Summary Report – full report for distribution in Q1 2018

Date: 20th December 2017

Dr Sheridan Few – Grantham Institute, Imperial College
Oliver Schmidt – Grantham Institute, Imperial College
Ajay Gambhir – Grantham Institute, Imperial College
Emma Stephenson – Shell Foundation
Amanda DelCore – Factor[E] Ventures

Shell Foundation

Grantham Institute
Climate Change and the Environment
An institute of Imperial College London

Table of Contents

Executive Summary

Over the past decade, there has been a rapid increase in the deployment of solar home systems, and rural utilities coupled with electrical energy storage devices, enabling off grid access to energy and power stability. Developments in the electric vehicle industry have led to significant innovation in energy storage technologies, increasing cycle life at the same time as reducing costs. However, selection of rapidly developing energy storage technologies for remote deployment has been a question of great debate in terms of technology selection and optimisation for performance, lifetime and costs.

This report presents outcomes from a series of interviews with organisations providing off grid energy solutions, on their storage technology choices, challenges and opportunities. These include insights on technology availability and supply chains, realised costs of storage solutions, performance of technologies and how these compare to manufacturers' specifications, and the environmental impact of storage technologies. Building on these insights, the report provides recommendations on how technology choices could be improved in the future, both from an individual company and from a regulatory perspective, and the impacts of future technology developments upon these choices.

Key takeaways

1. Energy storage technologies vary in terms of cost, cycle life, charge / discharge rate and environmental impact. Different business models and applications favour different technologies.

2. Lead-acid (PbA) and lithium-ion (Li-ion) batteries are the dominant storage technologies in all but the largest systems. Lead-acid batteries are mature and costs are relatively stable, whereas Li-ion battery costs are falling rapidly. In addition, Li-ion batteries have higher cycle life, and can charge / discharge faster than PbA batteries.

3. Companies using PbA batteries may switch to Li-ion batteries within the next 5-10 years as Li-ion becomes more cost competitive. Generally, applications requiring batteries of lower energy capacity switch first, owing to lower capital required per product.

4. PbA and Li-ion batteries are expected to remain dominant for at least the next ten years, but, other, less mature storage technologies such as Redox Flow Batteries (RFBs) are beginning to be commercialised and could be promising in the future.

5. Amongst Li-ion battery chemistries, those with lithium-iron-phosphate (LFP) cathodes are favoured owing to their safety and high cycle life in off-grid applications, in addition to their availability at relatively low costs from manufacturers in China and absence of toxic cobalt. However, quality of cells varies between manufacturers, and higher cost offers no guarantee of higher quality.

6. Li-ion batteries with nickel-manganese-cobalt (NMC) anodes, favoured in electric vehicle (EV) applications due to higher power and energy densities, could also be promising, particularly as costs fall and performance improves due to the scale-up of the EV market. But safety of such Li-ion chemistries in off grid applications has been questioned.

7. Thermal storage technologies, including thermal batteries, could become increasingly important at higher levels of energy access – particularly for agricultural refrigeration.

Key recommendations

1. There have been efforts to characterise the quality, cost and performance of different technology products in the off grid storage market, but greater quality and safety assurance, with the establishment of related standards, is required to enable appropriate, cost-effective and safe technology and product choice. This should extend to battery management and other battery electronics systems.

2. Measures to support the adoption of less mature technologies such as RFBs, which have been tested but not widely deployed, would help establish such technologies, enabling particular applications to benefit from their attributes.

3. Managing the environmental impact of storage technologies, particularly at end-of-life, represents a major gap. More detailed, effective and widespread regulation on end-of-life procedures, alongside supporting the emergence of a greater number of reputable, high quality and high safety recycling companies, would improve practice in this area.

1. Introduction

Over the past decades, a range of energy access services have emerged, partly driven by falling costs of solar photovoltaics (PVs) and battery storage [1]. These may broadly be broken down into five categories, each associated with a different scale of system. However, the process by which technologies are chosen for each application is not transparent, and it is not immediately clear which technology is most suitable for which application.

In this study, we interview representatives of a range of organisations involved in off grid energy supply in order to provide insight into the range of technologies used in rural electrification systems, costs of these technologies and associated business models, performance of technologies and how these compare to expectations and manufacturer specifications, supply chains and availability of technologies, and finally environmental impact and what steps are taken to minimise this.

We use insights arising from these interviews, alongside expertise in storage technologies from an academic perspective, to provide guidance on suitable energy storage technologies for a range of energy access services, to inform practice to minimise environmental impact, and to inform where innovation is required and where market level improvements could be beneficial to the sector.

2. Interview process

Following initial discussions with stakeholders in the off grid energy storage area, a semi-structured interview protocol was devised around technology choices, ensuring that key areas of interest were covered, whilst allowing sufficient space for interviewees to describe their own experiences. Names of organisations interviewed are presented in Table 1. Organisations were selected to provide a wide range of business models and applications in the off grid energy context. Each interview lasted between 1 and 2 hours. Owing to the geographically disperse nature of interviewees, most interviews took place remotely via conference call, and involved at least two of the report authors in order to ensure research themes were explored in sufficient detail.

Table 1 – Organisations interviewed in this study

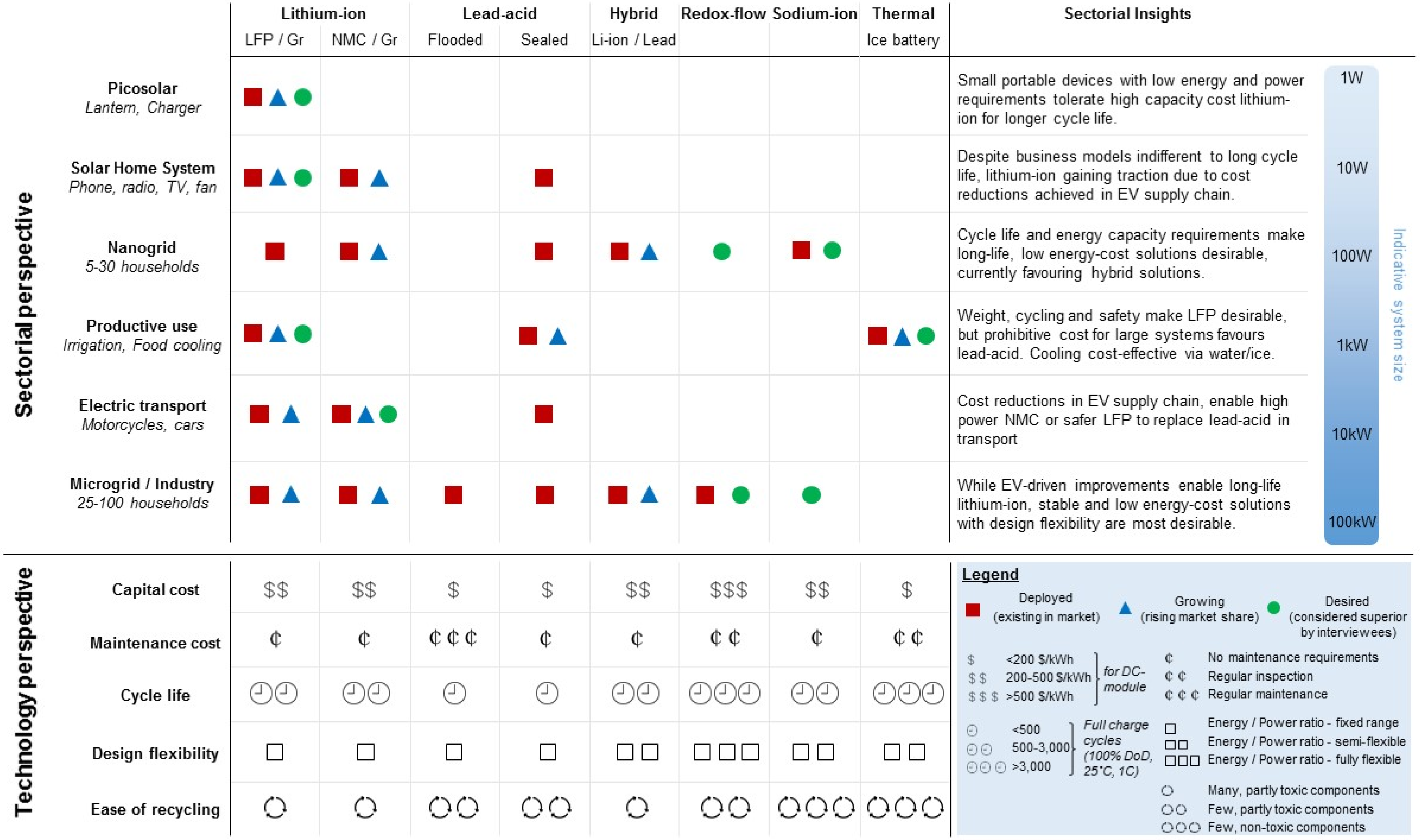
Organisation	Description	Location
BBOXX	Designs, manufactures and distributes solar home systems and larger solar systems for productive and business use, including consumer finance component (PAYG). Operates a true data driven business model and aims to replicate this globally. Approach to expansion into new markets; 'Build-Transfer-Operate' model takes equity stake in local partner for strategic alignment.	UK based, sales in 14 countries including experience across East Africa
BOS AG Balance of Storage Systems AG	BOS offers smart hybrid energy storage solutions and DC grid technology. With their technologies, large parts of the off-grid community in developing and industrialised countries get access to high-quality, long-lasting and affordable energy solutions.	Based in Germany with system deployed across Africa and India
CrossBoundary Energy	Invests, builds and operates solar installations for commercial and industrial uses – 0.05Mw-10Mw. Provides long-term power purchase agreements to supply cleaner and cheaper solar energy to established businesses. Aims to reduce buyers electricity cost by 30%+.	Kenya, Rwanda, Ghana, Nigeria
d.light	Design and manufacture affordable pico solar energy products, including PAYG option. Expanding range to fridges, fans & TVs. Innovative distribution models to reach low-income consumers & businesses.	Global
GOGLA	Not-for-profit industry association created to accelerate the growth of off-grid energy providers serving low-income households.	Global
Husk Power Systems	Designs, builds, owns & operates Solar/Biomass, grid compatible plants, providing 24 hour affordable power to households and businesses. Leader in the sector on experience, scale and unit economics.	India, Tanzania
Inficold	Deploys uninterrupted cooling systems operating on 5 to 8 hours electricity per day for milk cooling and agricultural produce. The systems are suited to bridge power outages or for coupling with intermittent power generation off-grid and can be retrofitted to any existing cooling system, thereby replacing diesel generators.	India
M-KOPA	Provides low-income consumers with asset financing to purchase energy products. Customers pay a small deposit and make daily instalments using mobile money. Creates a credit history for unbanked.	East Africa
Phenix Recycling	Collects electronic waste from a variety of industries including off-grid solar, bringing it to our factory for dismantling and dispose safely the waste that is generated with the highest safety and environmental standards.	East Africa
Redavia Solar	Modular solar farms - integrates with diesel systems (hybrid) to reduce emissions. Leasing model – with no upfront costs. Serves energy needs of industry, businesses & communities.	Tanzania, Kenya, Ghana
SunCulture	Designs, manufactures, sells, installs and finances low cost solar water pumps and irrigation products. Lowest cost solar pump on the market.	Kenya

3. Insights

3.1. Range of technologies

A range of technologies are used in off grid energy storage, and technology chosen varies by application, as shown in Fig. 1. Picosolar products typically make use of lithium-ion (Li-ion) batteries with lithium iron phosphate (LFP) cathodes. As systems become larger, the more mature lead-acid (PbA) battery becomes more favoured largely due to lower cost per energy capacity. Li-ion batteries are attractive due to their higher energy and power density and higher cycle life. Interviewed solar home system providers using PbA batteries had trialled Li-ion batteries, and were keeping a close eye on cost reductions, with an intention to switch when these become more economically viable.

Li-ion batteries with LFP cathodes were often favoured over those with nickel-magnesium-cobalt (NMC) cathodes due to the availability of lower-cost LFP cells from southern China, whilst NMC cells are typically sourced from the other regions at higher cost. Some interviewees perceived NMC cells as higher quality and more desirable, but prohibitively expensive. NMC cells have a higher voltage, and as such a higher energy density than LFP cells, but this may be associated with lower electrolyte stability leading to reduced cycle life and safety. As such, the LFP chemistry may be fundamentally a better choice for rural electrification systems where very high energy density is not required [2], but there may be a correlation between chemistry and quality of manufacture which may result in the opposite being the case for real world cells. LFP cells have the additional advantage of not requiting costly and environmentally damaging cobalt for their production. Sealed PbA batteries were typically preferred to flooded owing to lower maintenance requirements, and sodium-ion (Na-ion) and redox-flow batteries (RFBs) were used for some microgrid /industrial applications. These are currently less suitable for smaller scale systems, but could be promising in the future.



Sectorial perspective

	Lithium-ion LFP / Gr	Lithium-ion NMC / Gr	Lead-acid Flooded	Lead-acid Sealed	Hybrid Li-ion / Lead	Redox-flow	Sodium-ion	Thermal Ice battery	Sectorial Insights	Indicative system size
Picosolar *Lantern, Charger*	🟥 ▲ 🟢								Small portable devices with low energy and power requirements tolerate high capacity cost lithium-ion for longer cycle life.	1W
Solar Home System *Phone, radio, TV, fan*	🟥 ▲ 🟢	🟥 ▲		🟥					Despite business models indifferent to long cycle life, lithium-ion gaining traction due to cost reductions achieved in EV supply chain.	10W
Nanogrid *5-30 households*	🟥	🟥 ▲		🟥	🟥 ▲	🟢	🟥 🟢		Cycle life and energy capacity requirements make long-life, low energy-cost solutions desirable, currently favouring hybrid solutions.	100W
Productive use *Irrigation, Food cooling*	🟥 ▲ 🟢			🟥 ▲				🟥 ▲ 🟢	Weight, cycling and safety make LFP desirable, but prohibitive cost for large systems favours lead-acid. Cooling cost-effective via water/ice.	1kW
Electric transport *Motorcycles, cars*	🟥 ▲	🟥 ▲ 🟢		🟥					Cost reductions in EV supply chain, enable high power NMC or safer LFP to replace lead-acid in transport	10kW
Microgrid / Industry *25-100 households*	🟥 ▲	🟥 ▲	🟥	🟥	🟥 ▲	🟥 🟢	🟢		While EV-driven improvements enable long-life lithium-ion, stable and low energy-cost solutions with design flexibility are most desirable.	100kW

Technology perspective

	LFP / Gr	NMC / Gr	Flooded	Sealed	Li-ion / Lead	Redox-flow	Sodium-ion	Ice battery
Capital cost	$$	$$	$	$	$$	$$$	$$	$
Maintenance cost	¢	¢	¢ ¢ ¢	¢	¢	¢ ¢	¢	¢ ¢
Cycle life	🕒🕒	🕒🕒	🕒	🕒	🕒🕒	🕒🕒🕒	🕒🕒	🕒🕒🕒
Design flexibility	□	□	□	□	□ □	□ □ □	□ □	□ □
Ease of recycling	○	○	○○	○○	○	○○	○○○	○○○

Legend

🟥 Deployed (existing in market)
▲ Growing (rising market share)
🟢 Desired (considered superior by interviewees)

$ <200 $/kWh
$ $ 200-500 $/kWh
$ $ $ >500 $/kWh
for DC-module

¢ No maintenance requirements
¢ ¢ Regular inspection
¢ ¢ ¢ Regular maintenance

🕒 <500
🕒🕒 500-3,000
🕒🕒🕒 >3,000
Full charge cycles (100% DoD, 25°C, 1C)

□ Energy / Power ratio - fixed range
□□ Energy / Power ratio - semi-flexible
□□□ Energy / Power ratio - fully flexible

○ Many, partly toxic components
○○ Few, partly toxic components
○○○ Few, non-toxic components

Figure 1 - Deployed, growing and desired storage technologies in off-grid applications and technology characteristics. Sectorial perspective is based on interviews and reflects company views. Technology perspective reflects industry standard [3] and interview insights.

3.2 Cost of Technologies

The majority of cost information provided was for the two principal technologies currently used in off-grid and grid back-up systems, Li-ion and PbA. A variety of costs were reported, for a large range of battery sizes, reflecting the diversity of applications. In general there is no clear correlation between battery size and capital cost for either Li-ion or PbA batteries. The overall range of Li-ion battery costs is about $250-500/kWh, compared to $65-300/kWh for PbA batteries. In most cases the Li-ion batteries are for LFP chemistries, although in some cases precise chemistries were not specified. The PbA costs reflect both flooded and sealed varieties, again with precise technology not always specified.

In most cases respondents specified explicitly where inverters, battery management systems and other peripheral electronics would be additional to the capital costs above, but not in all cases. Caution is therefore needed in treating the costs above as on a like-for-like basis. In one case the respondent noted that the costs of the batteries they used were commercially confidential.

Respondents also commented on the additional costs associated with installing the systems, including transport and installation costs. In the case of transport costs, two respondents indicated that the international shipping cost (most commonly from China) was of the order $1-2 per unit (meaning battery, which could be up to a few kWh in size), so only about 1% or less of the overall battery pack cost. However, local transport costs varied depending on the remoteness and accessibility of the location. Installation costs were more significant, at around 5-10% of the overall battery or complete solar home system cost (if installed at the same time as the PV panel and other components).

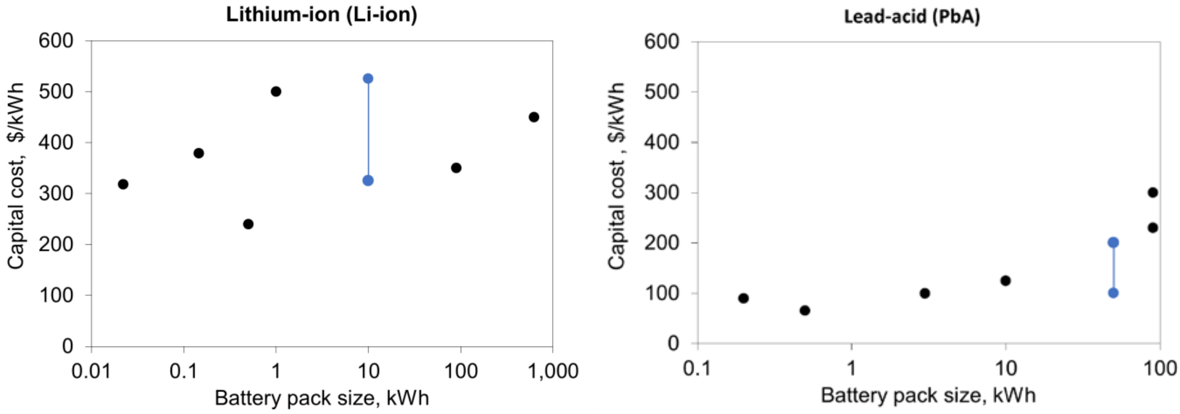


Figure 2 – Capital costs for DC-module of Li-ion (left) and PbA (right) batteries as reported by interviewees (black) and according to industry standard (blue) [3,4].

3.3. Performance of Technologies

Table 2 – Reported technology performance across a range of criteria

	Li-ion	**PbA**
Ease of installation and use	No reported issues.	Size and weight made transport to remote locations and installation on site challenging, particularly in agricultural applications.
Charge / discharge characteristics	Performance as expected.	Performance as expected, but one interviewee reported low current flow meant charge rate was slower than desired.
Round trip efficiency	Satisfied with as-expected 90%+ efficiency.	Satisfied with expected 75-85% efficiency. One interviewee reported a drop of 5-10% efficiency at operating temperature of 45^{o}C.
Cycle life	Limited experience of batteries meant full cycle life not tested. Discharge depths of 80-90% didn't appear to reduce cycle life, though higher temperature of operation does (as per PbA). One interviewee reported high charge / discharge rates reduced cycle life. In addition, users found large variability in cycle life performance between manufacturers.	One interviewee found a 10^{o}C higher-than-laboratory operating temperature leads to 50% decrease in cycle life). In addition, rapid charge / discharge and deep discharge affected cycle life significantly, with most restricting discharge depths to 50%.
Reliability	In general no major problems. One interviewee using LFP batteries indicated that their previous supplier provided an additional 10% of batteries to account for failures, but that failure rates were in some cases higher.	In general no major problems. One supplier making use of lead-acid batteries has found either very sudden, abrupt, failures (abrupt) or slow degradation with 1-2% fail within first 2 months.
Ease of expansion	In general easy to expand capacity as can add more batteries, but additional power is harder as requires updated electronics.	As per Li-ion
Safety	One interviewee indicated a preference for LFP over other Li-ion battery cathode chemistries due to higher safety levels than NMC electric vehicle (EV) cells and expressed particular concern around safety of second-life EV batteries.	One interviewee had experienced more safety issues with PbA than Li-ion batteries, and two interviewees indicated that issues can occur with production of hydrogen gas if PbA batteries are charged too quickly, which can lead to explosions without sufficient ventilation.

3.4. Availability of technologies

Interviewees reported that supply chains differ more with respect to energy access product provided than with electricity storage solution used for them. Hence, this section on supply chains is structured along the energy access product categories highlighted before.

There are hundreds of companies selling picosolar products, however around half a dozen serve the majority of the market. These companies differ in base (mostly Europe, USA, and China) and market integration (vertically integrated, focus on individual supply chain segment). What all companies have in common is that the Li-ion based products are manufactured in China. The vertically integrated companies engage in product design, may use contract manufacturing in China, and have own sales, marketing and distribution chains in their active markets. In case they do not fully control the retail level, they have distribution offices and mange last mile distributors and partner with micro-finance or operate on a pay-as-you-go (PAYG) basis. Some companies only manufacture the products and sell through traditional routes. But, vertical integrated companies that manage the whole supply chain tend to be more successful at building market share, despite significant challenge in building operations at all levels. While PAYG sales are becoming more important, over-the-counter (OTC) cash sales are still dominant.

Solar home systems are offered by around 30 companies, however the market is dominated by 10 to 15. Most providers purchase battery packs, but control the rest of the supply chain down to last-mile delivery. There are plentiful battery suppliers with up to 95% of those sold outside of India manufactured in South China (e.g. Guangdong), regardless of whether PbA or Li-ion. This is driven by manufacturing cost and skill in the region. In addition, PV panels and electronic communication devices are produced in that region, so existing relationships can be used. But, suppliers move from south to mainland China as regulations tighten with the mainland having less stringent ones. Wages are increasing as well, thus Vietnam, Cambodia and Malaysia might develop a larger manufacturing base. India is particular in that it has its own suppliers serving the domestic market for PbA batteries. Other manufacturers are based in Bangladesh or South East Asia (Thailand, Malaysia). Regarding Li-ion batteries, China is skewed to LFP-type. NMC-type batteries tend to come from East Asia (South Korea, Japan). Two sample supply chains are presented in Fig. 3.

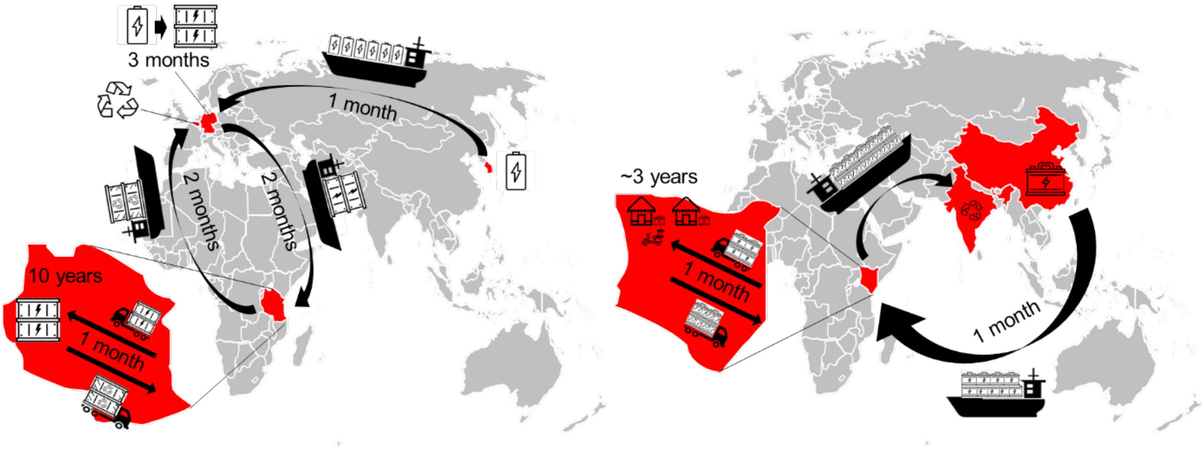


Figure 3 - Sample supply chain for **Left:** a minigrid supplier for rural electrification in Tanzania with a Li-ion battery. The Li-ion cells are shipped from South Korea to Germany where they are assembled to a containerised AC solution. The system is then shipped to Tanzania, where it needs to pass customs and is delivered to its place of operation by truck. Ideally, at its end of life, the battery system is disassembled and shipped to Belgium for recycling. In many cases, Li-ion batteries are currently dumped on landfills. Sample supply chain for **Right**: a solar home system technology provider in Kenya using lead-acid batteries. The batteries are manufactured in China and shipped to Mombasa, Kenya, from where they reach the shop via truck. Door-to-door delivery time is between 6-8 weeks. Last mile delivery to customer is performed by motorcycle. In case the battery is not refurbished and resold informally after its end-of-life, it gets shipped to India for commercial recycling.

3.5. Environmental Impact of Technologies and End-of-Life Procedures

Many organisations do not yet have an end-of-life procedure (Table 3). This is partly due to the rapid growth in the off grid market, and the limited number of systems which have reached their end-of-life, particularly those using Li-ion batteries. In addition, there is a lack of effective regulation or economic routes to recycling, with most interviewees reporting the major driver for recycling to be organisation ethos or reputation, rather than legal obligation.

Table 2 – End-of-life procedures

	Return to manufacturer	Pass to recycling bodies	No procedure established	No details provided
No. of respondents	1	2	3	2

Effective recycling procedures exist for PbA batteries in Europe and the US, where more than 95% of PbA batteries are recycled at the end of their lives, attributed to the profitability of reclaimed recycled materials, the illegality of disposing of batteries, the simplicity of disassembling the standard design of batteries and the simplicity of recycling the components. However, a high incidence of lead poisoning in other regions has been attributed to widespread informal lead-acid recycling without proper safety equipment [5–7]. Li-ion batteries could also be hazardous without proper recycling at the end of their useful lives [8]. Recycling procedures are not well established and are more challenging than for PbA batteries, owing to a more complex design and a wider range of materials used in their construction [9].

4. Discussion and Recommendations

With over 1 billion people lacking access to electricity, and continued reductions in cost of PV panels, Li-ion batteries and a range of other electricity and storage technologies, the off grid energy access industry is likely to continue its rapid growth for some years to come. As Li-ion costs fall, a gradual shift from PbA to Li-ion batteries may be expected in each sector, driven by longer lifetime and higher energy density. Lowest energy applications may be expected to switch earliest owing to capital costs remaining prohibitively high for longer in larger applications. In some applications, hybrid systems incorporating both PbA and Li-ion batteries are used and may be cost-effective for some time to come.

The sector is currently largely reactive rather than pro-active in terms of technology choices, making use of battery technologies already developed for other applications (Li-ion cells for electric vehicles in particular), and piggy-backing on improvements for these sectors. Quality assurance bodies and procedures exist, but many manufacturers do not participate in quality assurance programmes. A key recommendation is therefore for the establishment of more widespread quality, performance and safety standards and testing of storage technologies. This should extend to battery management and other battery electronics systems. In addition, although Li-ion and PbA appear appropriate for the majority of off grid electrification applications, a further key recommendation is for governments and market enablers to implement measures (whether pilot programmes, subsidies or other technology development and deployment measures) to support the adoption of less mature technologies such as RFBs, which have been tested but not widely deployed. This would help establish such technologies, enabling particular applications to benefit from their attributes.

Environmental impact at end-of-life represents a significant concern for these technologies. Absence of effective and detailed regulation on e-waste, as well as reputable, responsible, and safe recycling companies represent the two major ecosystem gaps which would allow for more effective recycling. As such, a key recommendation is for governments to implement effective regulatory procedures covering such e-waste. In addition, governments and market enablers should support the emergence of a greater number of reputable, high quality and high safety recycling companies.

About

Grantham Institute
Climate Change and the Environment
An institute of Imperial College London

The Grantham Institute at Imperial College is focused on driving research on climate change and the environment, and translating it into real world impact. The Institute's researchers are developing both the fundamental scientific understanding of climate and environmental change, and the mitigation and adaption responses to it. The research, policy and outreach work that the institute carries out is based on, and backed up by world leading research by academic staff at Imperial.

SHELL
FOUNDATION

Shell Foundation is an independent charity, established in 2000 by the Shell Group. We work to create and scale new solutions to global development challenges by applying business thinking to major social and environmental issues linked to energy and mobility.

Learning from both success and failure we have gradually developed a new "enterprise-based" model to catalyse lasting social and environmental impact on a global scale. This sees us deploy a blend of financial and non-financial resources to accelerate transformative innovation and harness private markets to deliver public benefit at scale.

Shell Foundation works with a small number of entrepreneurial partners to identify the underlying market failures behind intractable problems and co-create new enterprises to solve them. We provide patient grant funding, extensive business support and access to networks to help pioneers to validate new models, achieve financial independence and expand across geographies.

We then create specialist intermediaries to facilitate growth and replication at an industry level. By working in this way we now have several strategic partners – addressing issues as diverse as energy access, sustainable mobility and job creation through the SME sector – that are now delivering large-scale impact in multiple countries across Africa, Asia and Latin America.

Acknowledgements

We would like to thank the organisations that took the time to discuss in detail our survey and to share key opportunities and challenges with energy storage in the energy access sector.

References

[1] Kempener R, d'Orgitue O, Saygin D, Skeer J, Vinci S, Gielen D. Renewable Energy Systems: Status And Methodological Issues. 2015.

[2] Few S, Schmidt O, Offer GJ, Brandon N, Nelson J, Gambhir A. Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: an analysis informed by expert elicitations. Energy Policy 2018;[accepted].

[3] Kleinberg M. Battery Energy Storage Study for the 2017 IRP. Pacificorp; 2016.

[4] Matteson S, Williams E. Residual learning rates in lead-acid batteries: Effects on emerging technologies. Energy Policy 2015;85:71–9. doi:http://dx.doi.org/10.1016/j.enpol.2015.05.014.

[5] WHO | Lead poisoning and health. WHO 2017. http://www.who.int/mediacentre/factsheets/fs379/en/ (accessed December 12, 2017).

[6] Tian X, Gong Y, Wu Y, Agyeiwaa A, Zuo T. Management of used lead acid battery in China: Secondary lead industry progress, policies and problems. Resour Conserv Recycl 2014;93:75–84. doi:10.1016/J.RESCONREC.2014.10.008.

[7] Haefliger P, Mathieu-Nolf M, Lociciro S, Ndiaye C, Coly M, Diouf A, et al. Mass Lead Intoxication from Informal Used Lead-Acid Battery Recycling in Dakar, Senegal. Environ Health Perspect 2009;117:1535–40. doi:10.1289/ehp.0900696.

[8] Kang DHP, Chen M, Ogunseitan OA. Potential Environmental and Human Health Impacts of Rechargeable Lithium Batteries in Electronic Waste. Environ Sci Technol 2013;47:5495–503. doi:10.1021/es400614y.

[9] Gaines L. The future of automotive lithium-ion battery recycling : Charting a sustainable course. Sustain Mater Technol 2014;1–2:2–7. doi:10.1016/j.susmat.2014.10.001.

[10] Georg Fuchs, Benedikt Lunz, Matthias Leuthold, Dirk Uwe Sauer. Technology Overview on Electricity Storage: Overview on the potential and on the deployment perspectives of electricity storage technologies. 2012.

[11] Cluzel C, Douglas C. Cost and performance of EV batteries: Final report for The Committee on Climate Change. London: Element Energy; 2012.

[12] Sodium-ion battery. 2016.

[13] Komaba S, Ishikawa T, Yabuuchi N, Murata W, Ito A, Ohsawa Y. Fluorinated Ethylene Carbonate as Electrolyte Additive for Rechargeable Na Batteries. ACS Appl Mater Interfaces 2011;3:4165–8. doi:10.1021/am200973k.

[14] IRENA-IEA-ETSAP Technology Brief 4: Thermal Storage. IEA-ETSAP and IRENA; 2013.

[15] Product Overview n.d. http://www.inficold.com/products.html (accessed December 14, 2017).

Appendix – Technology Description

Lead-acid batteries consist of lead dioxide (cathode), metal lead (anode) and aqueous sulphuric acid (electrolyte). When discharging, the sulphuric acid is consumed, converting each electrode to lead sulphate. This process is reversed during charging. Lead-acid batteries are the world's most widely used battery type and have been commercially deployed since about 1890, and are a mature technology with the lowest capital cost per energy capacity of storage technologies considered here. However, the cycle life is low compared to competing technologies, resulting in increased cost per energy stored over battery lifetime, and their energy density is relatively low, making them bulky and difficult to manoeuvre. There exist two main variants of lead-acid battery:

- Flooded, in which electrodes are immersed in in liquid electrolytes.
- Sealed, in which electrodes are replaced with a gel or soaked glass fibre.

Flooded lead-acid batteries are typically cheaper, and have longer lifetime than sealed batteries, but require more maintenance and exhibit lower safety levels.

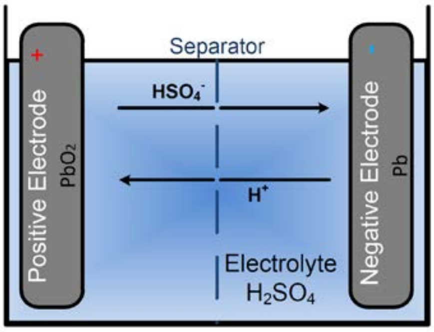


Figure 4 - Principle of the discharge and charge process in a Lead-acid cell [10]

Lithium-ion batteries consist of a number of lithium ion cells together with electronics for battery management. During charging and discharging, lithium ions suspended in an electrolyte shuttle between a cathode and anode within the cells. Lithium-ion batteries are relatively mature for portable electronics applications, but less mature for electric vehicles and off--grid stationary applications. They have relatively high cycle life, respond quickly demand and high volumetric and gravitational energy densities. Costs of Li-ion batteries for electric vehicles is decreasing rapidly, which is having knock-n effects for costs of batteries in an off-grid context, but remain higher than lead-acid in terms of capital cost per energy capacity. Properties of lithium-ion cells vary significantly depending on material used for the anode and cathode[11].

- LCO/Gr Lithium ion cells using lithium cobalt oxide (LCO) cathodes with graphite (Gr) anodes. These cells were the first commercialised rechargeable lithium-ion cell type, are widely used in portable electronics applications. However, safety issues in larger battery systems, and relatively low cycle life, make these cells unsuitable for electric vehicles and solar home (and larger) systems.

- NMC/Gr Lithium ion cells using lithium nickel manganese cobalt oxide (NMC) cathodes with graphite (Gr) anodes exhibit higher levels of safety and higher cycle life than LCO cells, whilst having relatively high energy and power densities. This combination of characteristics makes this cell chemistry a popular choice for EV applications.

- LFP/Gr Lithium ion cells using lithium iron phosphate (LFP) cathodes with graphite (Gr) anodes, most commonly produced in China due to constraints on cobalt supply preventing widespread production of batteries with cobalt-containing cathode materials. This cell chemistry has a slightly lower energy and power density than NMC, owing to a lower cell voltage. However, this chemistry is reported to have excellent thermal and chemical stability, and exhibits relatively long cycle life (perhaps associated with increased electrolyte stability due to the lower cell voltage).

- LFP/LTO Lithium ion cells using lithium iron phosphate (LFP) cathodes with lithium titanate (LTO) anodes exhibit exceptionally high levels of safety, long cycle life, and tolerance to rapid charge/discharge. However, they have a relatively low cell voltage and consequently a low energy density compared to other lithium-ion chemistries (making them less suitable for small to medium sized electric vehicles). Whilst commercial cells exist, this chemistry is relatively commercially immature compared to others discussed here, and costs so far remain relatively high.

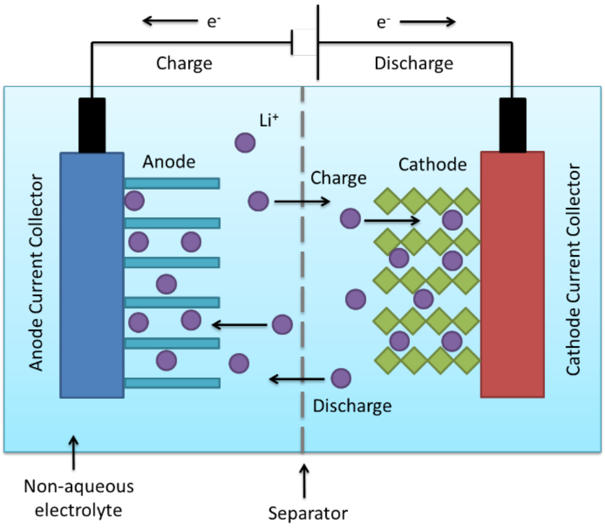


Figure 5 - Schematic intercalation and de-intercalation of lithium in anode / cathode of a lithium-ion battery cell [2]

Redox-flow batteries use two liquid electrolytes, one positively charged, and one negatively charged as energy carriers. The electrolytes are separated using a membrane, which selected ions pass through and undergo chemical reactions during charge and discharge. The electrolytes are stored in separate tanks and is pumped into the battery when required, allowing the size of electrolyte tanks to define capacity. Vanadium redox flow batteries (VRFBs) using vanadium electrolytes represent the most mature redox flow technology. Redox flow batteries have the potential to operate at a range of scales, including in a large scale grid context, and an off-grid context. The high cycle life of VRBs makes them promising in terms of cost for long-term applications. Redox flow batteries (RFBs) also offer the potential to decouple power and energy capacity, making them particularly versatile in terms of design. However, this technology has been less widely commercialised than competing technologies, particularly on an off-grid scale, and mass and volume densities are too low for EV applications.

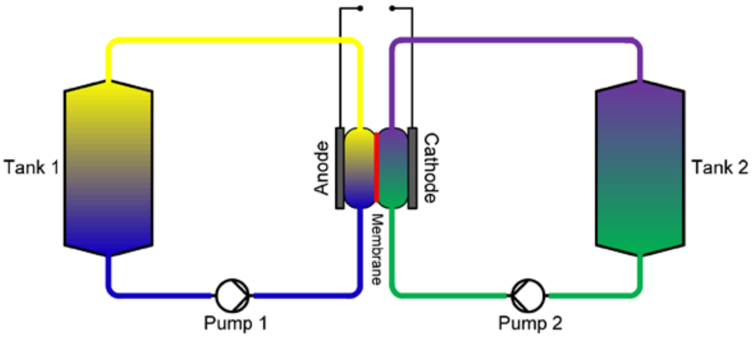


Figure 6 – Schematic design of a redox-flow battery [10]

Sodium-ion batteries store electricity based on electrochemical charge/discharge reactions that occur between a positive electrode (cathode) composed of sodium-containing layered materials, and a negative electrode (anode) that is typically made of hard carbons or intercalation compounds[12]. The electrodes are separated by porous material which allow ionic flow between them and are immersed in an electrolyte that can be aqueous (such as Na_2SO_4 solution) or non-aqueous (e.g. salts in propylene carbonate). When the battery is being charged, Na atoms in the cathode release electrons to the external circuit and become ions which migrate through the electrolyte toward the anode. There they combine with electrons from the external circuit while reacting with the layered anode material. This process is reversed during discharge.

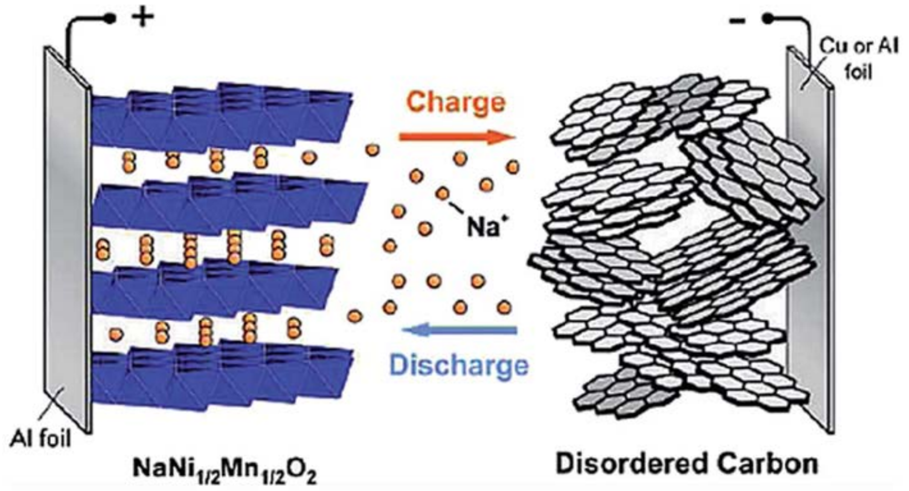


Figure 7 - Schematic of sodium ion batteries with a layered transition metal oxide cathode and carbonaceous anode [13]

Thermal energy storage can be provided from a storage reservoir directly or indirectly. Cold storage refers to the cold stored in materials, for example ice cubes that can be used directly to provide the thermal energy. The concept of storing energy in batteries (electrical) or biomass (chemical) to provide thermal energy indirectly with a conversion technology is also common.

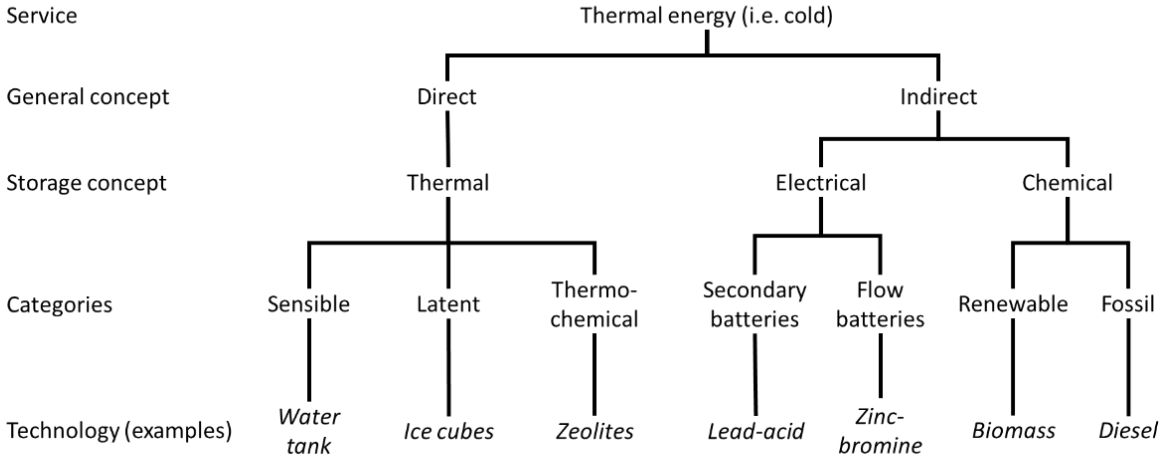


Figure 8 – Different technology pathways to providing thermal energy.

The three direct cold storage categories are [14]:

Name	**Description**	**Advantage**	**Disadvantage**
Sensible (e.g. water)	Thermal energy consumed/ released during temperature change	Simple, mature, cheap	Large volumes, small op. range
Latent (e.g. water – ice)	Thermal energy consumed/ released during phase-change at constant T	Small volumes	
Thermo-chemical (e.g. zeolites)	Thermal energy consumed/ released during chemical reactions	Small volumes, seasonal storage	Novel, immature

While the material that absorbs thermal energy by changing its characteristics is key to any cold storage technology, other important components can be the heat exchanger, heat transfer fluid, energy conversion device, storage container and ancillary components (pumps, valves, pipes, etc.).

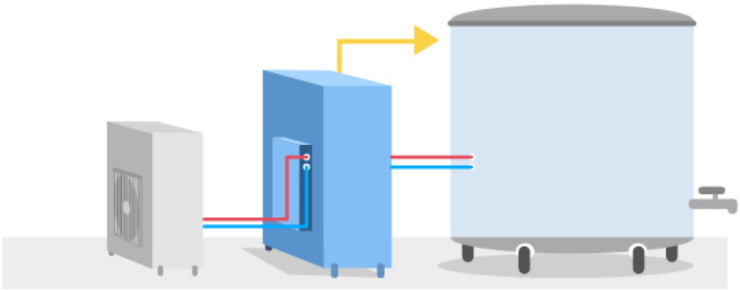


Figure 9 – Sample cold storage technology, where cold store (middle) was cooled via compressor (left) when electricity was available (in parallel to cooling the tank) and directly cools tank (right) during an outage [15] without requiring electricity.