Energy storage trends for off-grid services in emerging markets

Insights from social enterprises

Final Report

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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.

Executive Summary

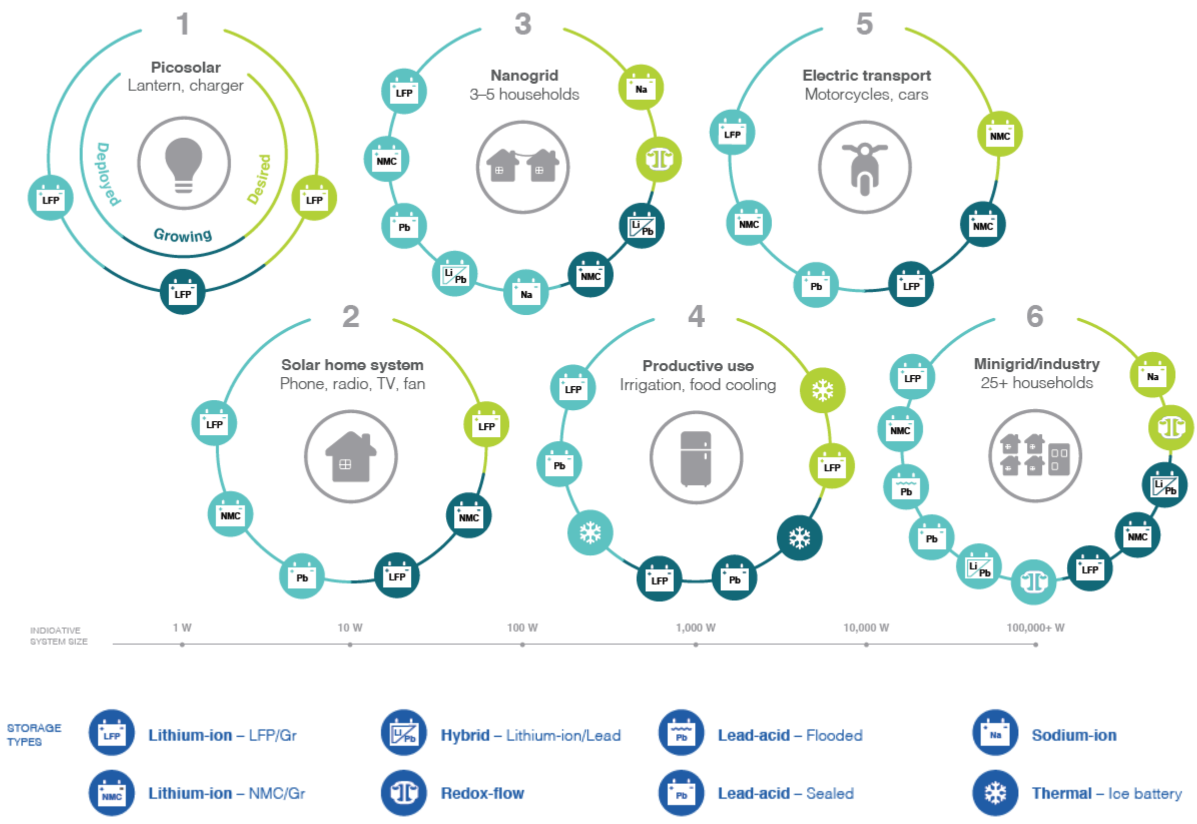
Energy storage has become a key issue for renewable energy sectors. Shell Foundation and the Grantham Institute at Imperial College, London, have collaborated on this report exploring solutions for off-grid energy organisations, looking at technology choices, challenges and opportunities. Over the past 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.

It is recognised that that continued reductions in costs in lithium-ion batteries are expected to drive increasing competition with lead-acid batteries over the coming years. This means that lithium-ion batteries are expected to become dominant in solar home systems in the next 5 – 15 years. Cost reductions in NMC (Nickel Manganese Cobalt Oxide) based lithium-ion batteries for electric vehicle applications may make them more competitive relative to Lithium iron phosphate batteries over a similar time period. Hybrid lead-acid/lithium ion systems for larger systems may grow in their usage and continue to represent the most viable option for nano/minigrid systems. Other battery systems in early commercialisation or R&D phases, such as sodium-ion or flow batteries, may come to play a significant role further in the future if they are able to compete on cost terms. However, owing to long time periods associated with both R&D breakthroughs and going from first commercial products to widespread usage, this is unlikely to occur within the next decade, given that there is inherent risk in sourcing new battery chemistries so as to provide a reliable, field-tested product. Research findings included analysis that was complete at a sector level and at a technology level resulting in a summary of key takeaways from the report.

Key takeaways

1. **Sector perspective:**



Picosolar – Small portable devices with low energy and power requirements tolerate high capacity cost lithium-ion for longer cycle life

Solar Home System – Lithium-ion gaining traction due to cost reductions achieved in electric vehicle (EV) supply chain

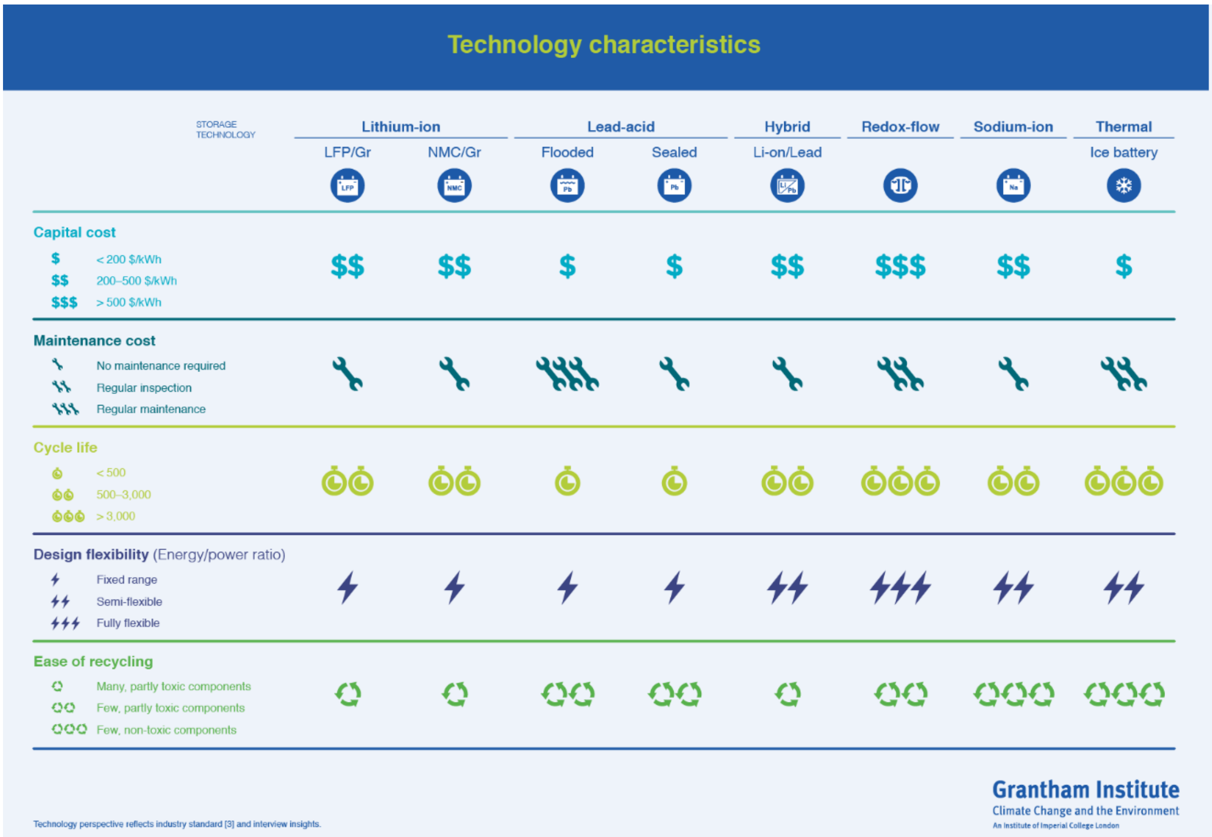
Nanogrid – Cycle life and energy capacity requirements make long-life, low-cost solutions desirable, currently favouring hybrid solutions

Productive use – weight, cycling and safety make lithium iron phosphate desirable, but prohibitive cost for large systems favours lead-acid. Cooling is cost effective via water/ice.

Electric transport – cost reductions in EV supply chain enable high power NMC or safer LFP to replace lead-acid in transport

Minigrid/ Industry – While EV-driven improvements enable long-life lithium-ion, stable low-cost solutions with design flexibility are most desirable

2. Technology perspective:



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. The energy access industry is relatively risk averse and largely reactive in terms of storage technology choices, relying on cost and performance improvements achieved in other industries (like EV industry).
3. Five main drivers that determine the choice of storage technology for applications in developing countries:
    i. Commercial readiness
    ii. Capital cost
    iii. Technology performance
    iv. Financial stability of provider
    v. Future orientated technology
4. 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.

5. 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.
6. 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.
7. 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.
8. 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. However, the safety of such Li-ion chemistries in off grid applications has been questioned.
9. Thermal storage technologies could become increasingly important at higher levels of energy access – particularly for agricultural refrigeration.

<u>Key recommendations</u>

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.

A range of energy storage technologies are used in energy access contexts. Their key characteristics are described below:

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 liquid electrolytes.
- Sealed, in which electrodes are rep
- laced 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.

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 to demand and have high volumetric and gravitational energy densities. Costs of Li-ion batteries for electric vehicles is decreasing rapidly, which is having knock-on 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 [cit Cluzel&Douglas]:

- **LCO/Gr** Lithium ion cells using lithium cobalt oxide (LCO) cathodes with graphite (Gr) anodes. These cells which 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.

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 are 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.

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.

Electricity storage products for applications in off-grid or weak-grid environments can be categorised into five groups[1]:

Picosolar products can go up to 10 W with storage capacities of 1 to 40 Wh. They are designed to provide lighting and sometimes cell phone charging. Expected lifetimes range between 3 to 10 years. These devices were among the first solar products introduced in developing countries with quality-verified solar lanterns having reached cumulative global sales of 20 million since 2010[2].

Solar home systems range from 5 W to 350 W with typical storage capacities of 20 to 200 Wh. On average the systems are charged and discharged once a day. While smaller systems are only for lighting and phone charging, larger ones can power additional appliances such as radios, fans or TVs. For most products, appliances are locked into the system, which means that external appliances cannot be connected. This is to ensure operability and to bind customers for future upselling. The systems are sold on lease-to-own or pay-as-you-go (PAYG) schemes [2].

Productive use products enable agricultural and industrial value creation or further increase production efficiency in off grid communities. Solar irrigation pumps are a prime example and can be grouped into large pumps for commercial agricultural use (300 W to 1500 W, 300 charge/discharge cycles per year) and small pumps for smallholder farmers and domestic agricultural use (70 W to 300 W, 150 charge/ discharge cycles per year). Future applications for productive use products could be post-harvesting equipment like food processing or cooling.

Nanogrids range between 300 W and 5 kW and can serve 5-30 households. They are direct current (DC) systems providing power for domestic applications such as phone charging, radio and TV. Thus, they could be seen as large-scale solar home systems connected to multiple households[2]. Due to scale and portfolio effects, pricing models can be more competitive than for individual solar home systems in some instances.

Minigrids can go up to 100 kW and serve entire villages of 25 to 500 households[2]. They are operated with alternating current, which requires an inverter for the PV power source, but also means they can easily be combined with thermal power sources such as biomass plants or diesel generators. Therefore, minigrids can also be a solution for more developed, urban regions where customers have high power consuming AC devices already (Fridge, TV, etc.), and for densely populated, developed off-grid areas.

Industry applications overlap in system size with minigrids, and include powering off-grid areas with regular large-scale power consumers (e.g. telecommunication towers and spinning reserve for mines), balancing supply of solar power from solar farms, providing backup power for grid-connected businesses.

[1] System sizes in each case reflect the range found in products offered by interviewed participants, and should be considered as indicative rather than definitive. Systems offering higher power/energy services are likely in general to be larger.

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 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. 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	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 their factory for dismantling and safe disposal of 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.	Across Africa

Twelve interviewees were selected to provide a wide range of business models and applications in the rural electrification context. These included two companies active in provision of picosolar products, four in solar home systems, one in productive use, three in nanogrids, and two in minigrid/industry (some interviewed organisations were active in more than one of these areas). Our interview pool also included one e-waste collection and recycling organisation, one industry association, and two developing thermal storage technologies for refrigeration. Commercial organisations were predominantly active in East Africa, but also included some operating in other parts of Africa, and in India. A range of business models were used, including pay-as-you-go, lease-to-own, direct sale, and sale of systems to intermediaries who are responsible for last-mile delivery and financing.

3. Interview insights

3.1 Range of electricity storage technologies in energy access applications

Company considerations in choosing technology

We identified five main drivers that determine the choice of storage technology for applications in developing countries:

1. Commercial readiness
2. Capital cost
3. Technology performance
4. Financial stability of provider
5. Future-orientated technology

The most important driver is **commercial readiness** of the product. The energy access sector is reactive to developments in storage technologies and testing of novel technologies in this business environment is perceived as too costly and risky. Proven technology is used as it best guarantees feasible lifetimes and low failure rates in remote and environmentally harsh conditions. Warranties provide a safeguard for businesses and are thus a key element to any technology that will be used.

Capital cost is another key driver. While one technology might be best-suited for an application in terms of lifetime cost or technology performance, another is chosen due to difficulties in paying the high upfront cost for the first.

A related driver is **technology performance** and its suitability to the respective application. For example, when considering a short operational life (3-5 years), lead-acid is preferred due to low capital costs at suitable cycle life performance. If a business case requires long operation (5-10 years, e.g. a solar home or minigrid system), then lithium-ion is considered given its extended lifespan and robustness to extreme temperatures and deep discharge cycles, but in practice may not be chosen due to high upfront capital cost. In applications, where high charge / discharge rates, little energy storage capacity and many cycles are required, lithium-ion is likely to be preferred, despite potentially higher upfront capital costs.

A key decision criterion is also the **financial stability** of the storage technology provider. Many interviewees told of initial technology choices that failed due to bankruptcy of the technology provider. This resulted in increased scrutiny of the financial stability of any following technology providers and the preference to work with established players. So, while desired technologies are available in target markets, the financial stability of their providers hinders their deployment.

A final criterion related to the nature of companies active in the energy access industry, i.e. start-ups, is the interest in **future-orientated technologies** and the desire to test technologies with different characteristics. This is driven by the companies' funding structure (e.g. grants) and strong focus on novelty and future growth potentials.

Environmental aspects are somewhat taken into consideration when choosing the technology.

Overview on energy access applications

A range of technologies are used in rural electrification (see Fig. 2), and technology chosen varies by application. Broadly speaking, lead-acid and lithium-ion are dominant for all but the largest considered applications. Picosolar products typically make use of lithium-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 its lower cost per capacity. Lithium-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 lithium-ion batteries, and were keeping a close eye on cost reductions, with an intention to switch when these become more economically viable. Regarding technology sub-type, LFP is predominant within those companies using lithium-ion batteries, although NMC is beginning to be used as well. For lead-acid, sealed batteries dominate over flooded ones, largely due to lower maintenance requirements.

Of the 12 companies interviewed, eight are actively deploying electricity storage technologies for energy access applications. Figure 1 shows the energy access product categories they are active in. We identified a trend regarding technology penetration in the different energy access product categories that is presented qualitatively in Figure 2.

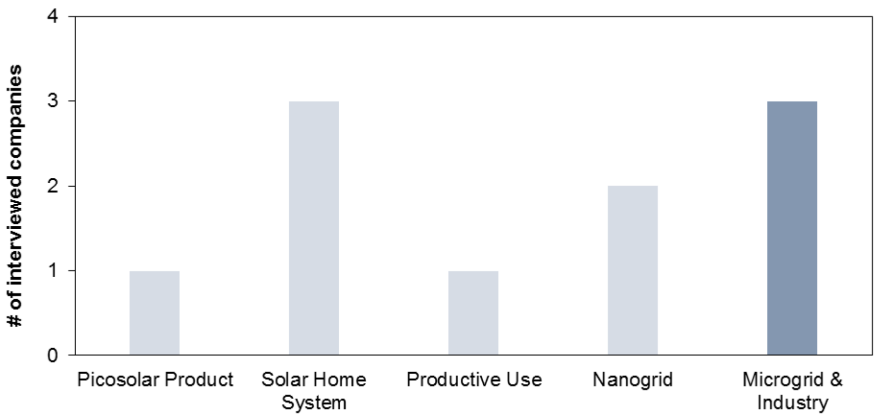


Figure 1 – Number of interviewed companies active in the different energy access product categories. Grey and blue categories predominantly operate with DC- or AC-systems respectively.

For **picosolar products** the last 10 years have seen a shift from lead-acid to nickel-metal hydride and now lithium-ion based batteries. The vast majority of these products is now equipped with lithium ferro phosphate (LFP) batteries.

A shift from lead-acid to lithium-ion can also be observed in **solar home systems (SHS)**. LFP-type lithium-ion batteries are being increasingly used for smaller batteries (20-30W), outpacing industry expectations. This is the result of longer lifetimes, reduced costs and similar voltage characteristics to lead-acid, that make LFP lithium-ion compatible with existing SHS devices. Most business models are driven by end-user finance like PAYG, because low payments for longer terms can significantly increase the customer base. Hence, longer cycle life technologies have an advantage. Some companies are also considering nickel manganese cobalt (NMC) instead of LFP. This is driven by product reliability and the cost reductions large, international suppliers have achieved in electric vehicle battery pack manufacturing. In the energy access business, this is particularly relevant for larger battery systems where the reduced weight of NMC batteries can be an advantage and high charge and discharge rates are required. It is also a prime example of how the energy access industry is largely reactive, relying on cost and performance improvements achieved in other industries (like the EV industry).

Productive use products are an example for the remaining competitive edge of lead-acid over lithium-ion. One interviewed company that initially considered LFP for its 15 Who batteries, switched to sealed lead-acid when realising that customers required 500 Wh systems. The lower capital costs of lead-acid (3-4x) become significant for medium to large-scale applications with high upfront costs, despite much shorter lifetimes. Any future cost reduction for lithium-ion is assumed to increase its relevance for larger systems though.

Nanogrids and **minigrids** are also still dominated by lead-acid batteries due to the high upfront capital cost for large systems. This dominance is again challenged by lithium-ion for smaller systems where upfront costs are less relevant. Also, applications that require high power-to-energy ratios see more NMC lithium-ion batteries installed due to the higher possible charge / discharge rates (e.g. For high power to energy ratio application an example would be the avoidance of business interruption due to grid failure or diesel gen set tripping). Redox-flow batteries were already chosen for energy-focussed minigrid applications that require long lifetimes. However, the deployment of this technology failed due to the financial immaturity of existing providers. Sodium-ion batteries were ordered by two interviewed companies. But, the batteries were either damaged during delivery or the supplier of the operational system is no longer in business.

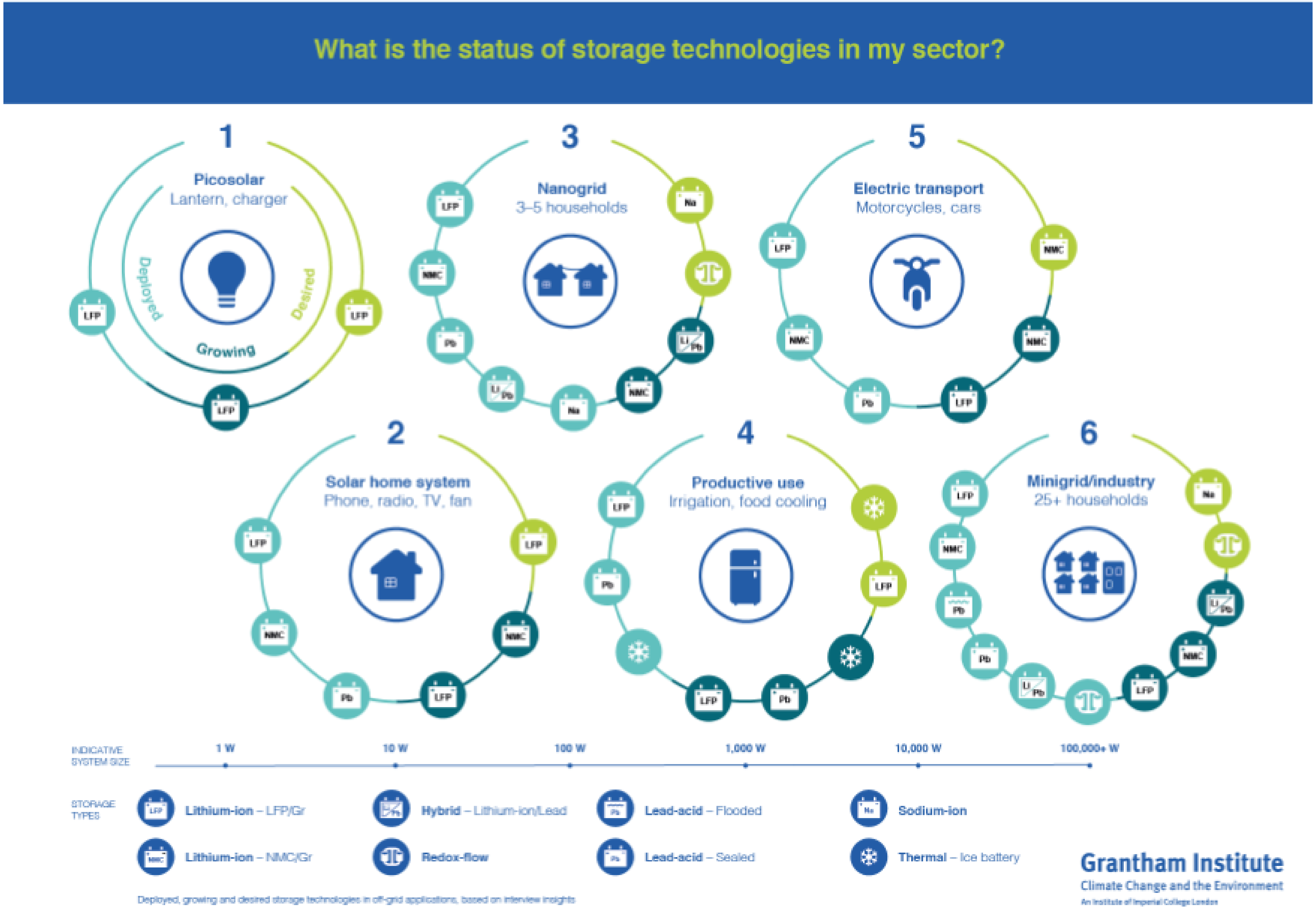


Figure 2 - Deployed, growing and desired storage technologies in off-grid applications. Sectorial perspective is based on interviews and reflects company views.

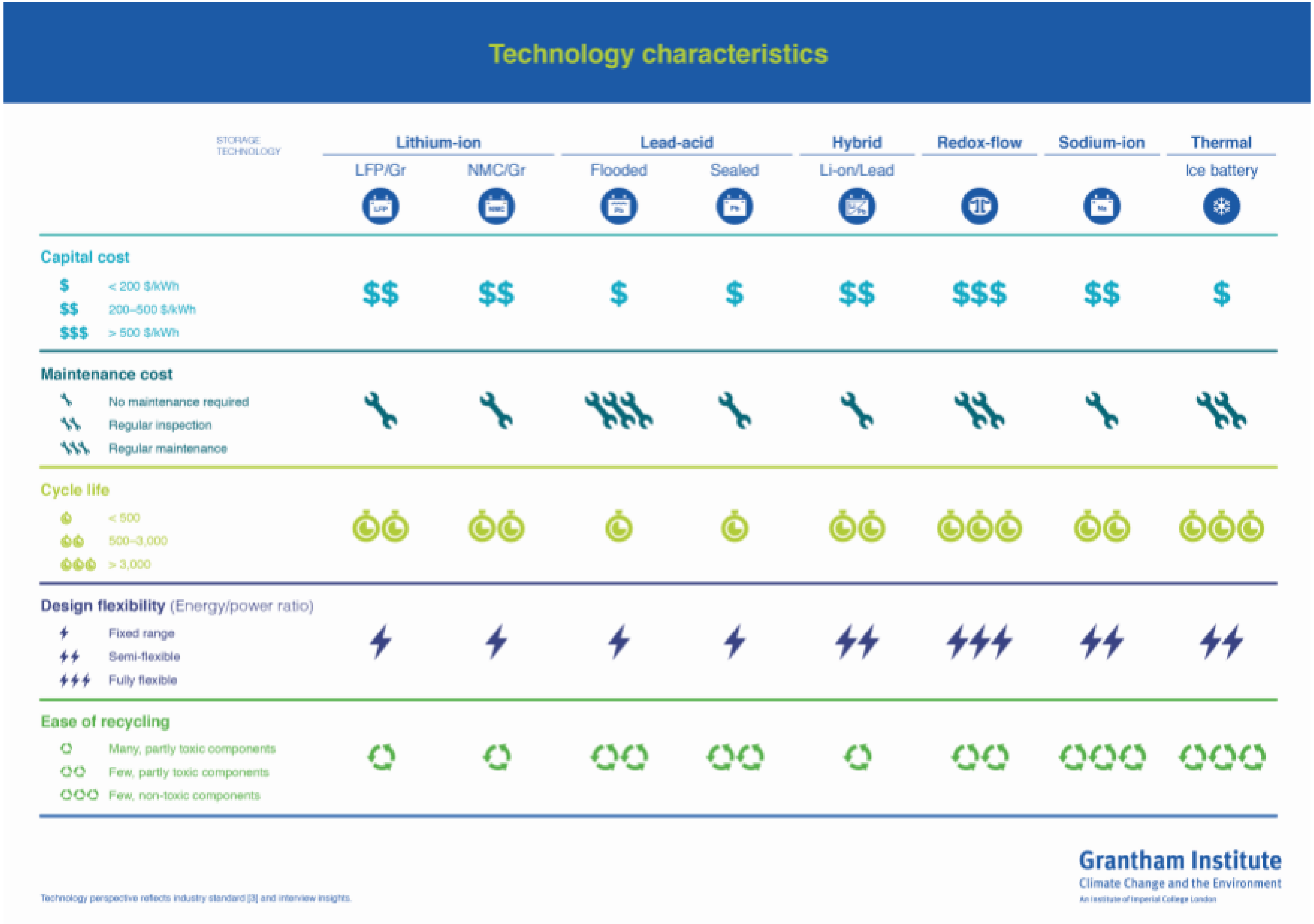


Figure 3 - Technology characteristics. Technology perspective reflects industry standard [3] and interview insights

Characteristics of current storage technologies used

Figure 2 and 34 summarise the current status and technical performance of dominant technologies in energy access applications.

Lead-acid batteries are cheapest and most mature, which makes them the technology of choice for large-scale, capex-heavy projects. However, they also have significant shortcomings for energy access applications. The batteries take up much space and require many modules for large systems due to the low power and energy density, necessitating connections between modules that lead to state-of-charge deviations due to voltage discrepancies between strings. The unsuitable power-to-energy ratio means that for many applications, lead-acid batteries cannot be discharged quickly enough, but provide energy for longer than needed. Also, cycle life is relatively short and high temperatures or deep discharge cycles further reduce it. One interviewee mentioned the danger of theft due to the value of lead-acid batteries in the informal market, which apparently made one operator build concrete casings around for them to prevent theft at a telecommunication tower.

Lead-acid batteries can be differentiated into **Flooded** and **Sealed** lead-acid. Valve-regulated **(VRLA)** and absorbed glass matte **(AGM)** are common sealed lead-acid battery types that are frequently used in off-grid applications. While flooded batteries are cheaper, they require regular topping-up of water and are more prone to faults than sealed ones.

Interviewees consider **Lithium-ion** batteries “smarter” as their high power and energy density means they are more lightweight and require less modules for desired performance, which translates into easier integration into the battery system for larger systems. For small-scale systems the additional advantage is that the relatively high capital costs become less significant and instead the longer lifetime and ability to operate at high temperatures and discharge deeply become deciding factors.

The most common lithium-ion chemistry used in off-grid applications is lithium ferro phosphate **(LFP)**, but nickel manganese cobalt **(NMC)** is also considered. LFP is non-toxic and cheaper than NMC, and its slightly higher energy density is not as important an issue for stationary applications as for mobile applications. NMC is considered slightly less safe and more prone to thermal runaway potentially leading to fires and explosion. However, performance and cost improvements by large, reliable manufacturers in the context of electric vehicle battery pack manufacturing, make this lithium-ion type a potential alternative to LFP. Smaller footprint and even lower weight due to the higher energy and power density are an additional benefit, contrasted by higher capital costs for energy storage capacity. Novel lithium-ion chemistries like lithium titanium oxide (LTO) are still considered too immature and expensive for off-grid applications.

Hybrid systems can combine the cycle life and charge rate advantage of lithium-ion with the low-cost energy capacity of lead-acid. While the lithium-ion battery will be cycled daily, the lead-acid battery serves as back-up using a maximum of 20% of its capacity daily and more of that on a weekly basis to supply peaks. In this solution, optimal power-to-energy ratios of the battery can be designed with lifetimes of 8 to 10 years.

Redox-flow batteries have the intrinsic advantage of full design flexibility regarding power (kW) and energy (kWh) capacity that can be specifically tailored to any application. This modularity, enabling flexible energy or power capacity additions, makes the batteries particularly suitable for energy-focussed applications like rural electrification minigrids. There is no capacity degradation, allowing unlimited cycling, but corrosion effects limit lifetimes to 15 years, which could still match the lifetime of the solar power source better than other storage technologies. The salvage value of the non-degraded electrolyte is an additional cost-benefit and could ensure proper disposal. However, the technology is still in its infancy with a few pilot projects around the world run by a handful of start-ups. As a result, limited operational experience and financially unstable providers limit the deployment of this technology, in particular in energy access applications.

Interviewees couldn't comment in detail on the advantages and disadvantages of **sodium-ion** batteries due to lack of experience. Generally, it was mentioned that they are very environmentally benign, but suffered from high failure rates in developing market context and immature suppliers.

<u>Emerging storage technologies</u>

Lithium-ion batteries are already dominant for smaller picosolar products and are increasingly deployed in larger solar home systems. Nearly all interviewees agreed that lithium-ion will continue to grow to become the dominant storage technology in larger energy access applications in the next 5 - 10 years, because of its superior performance characteristics to lead-acid, industry scale and cost reduction potentials.

A near-term transformation that could take place is the increased uptake of **NMC**- rather than **LFP-**type lithium-ion batteries due to its imminent up-scaling in electric vehicle (EV) battery pack manufacturing. However, this remains subject to uncertainty, and growth in production of LFP-type lithium-ion batteries may also continue.

Second-life EV lithium-ion batteries were also mentioned multiple times as a cost-effective and suitable solution for stationary energy access application with lower performance requirements than EVs. However, this option is highly dependent on the uptake of EVs. At the moment, only few second-life batteries become available each year and no actual product exists.

Redox-flow batteries are potentially suitable for applications requiring large energy storage capacities at moderate power requirements. However, a reliable and financially stable supplier with a track record of installed systems does not yet exist.

Some interviewees had experience with **sodium-ion** batteries and, despite high failure rates and bankrupt suppliers, still considered this technology a potential solution in the medium-term. Similarly, to redox-flow, a mature supplier is missing, while the technology itself appears more immature. All interviewees agreed that it could be the most environmentally benign one though.

Other technologies that were mentioned as being in pilot plant stage with potential breakthroughs in performance and cost within the next years were:

- Advanced lead-acid
- Zinc-air
- Long-storage flywheels
- Solid-alkaline batteries

3.2 Costs of technologies

The majority of cost information provided was for the two principal technologies currently used in off-grid and grid back-up systems, i.e. Li-ion and PbA. A variety of costs were reported, for a very large range of battery sizes, reflecting the great diversity of applications for these storage technologies as discussed in Section 3.1. In limited cases costs were also reported for other technologies including Redox Flow batteries and also saltwater (sodium-ion) batteries. The following sub-sections first discuss the relative capital costs of batteries, before then discussing recent reported cost reductions in the different battery technologies, as well as other relevant cost-related information.

<u>Capital costs</u>

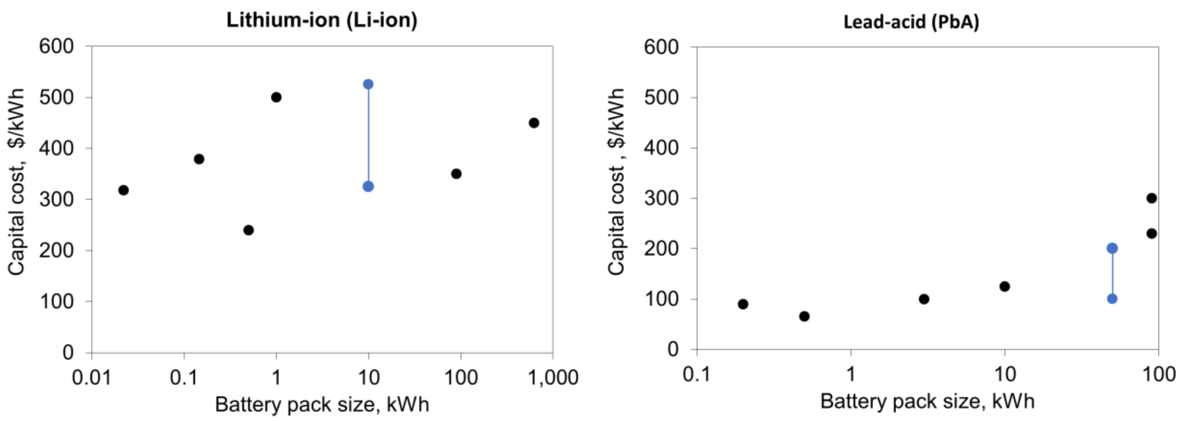


Figure 4 – Capital costs (in $ per unit capacity i.e. $/kWh) for DC-module of Li-ion (left) and PbA (right) batteries against typical battery capacity (on a logarithmic scale) as reported by interviewees (black) and according to industry standard (blue) [3,4].

In general, there is no clear correlation between battery size and capital cost for either Li-ion or PbA batteries. Ignoring outliers, Figure 4 shows the overall range of Li-ion battery pack costs is about $250-500/kWh, compared to $65-300/kWh for PbA batteries (full set of data points in appendices). 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 specified in some cases.

It was unclear from some respondents what components were included in the overall capital cost. 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. Costs also differ per total kWh purchased depending on volume of order.

Respondents also commented (where they had available information to hand) 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 transport cost (including shipping, most commonly from China) was of the order $1-2 per unit (with a unit meaning a 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 within-country 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).

It should be noted that capital cost is not the sole criterion on which to judge the overall cost-competitiveness of each technology – one respondent noted that the capital cost of Li-ion batteries may be higher than PbA, but their higher power output per kWh of capacity (compared to PbA) made them less costly for the particular application (to replace spinning reserves).

Additional technology costs were also reported, for currently more niche / less mature technologies. One respondent reported receiving quotes of Redox Flow Batteries (RFBs) of $170/kWh, but sceptically noted that this was not credible at this time and might be cost-minus pricing. A more detailed quote for RFBs came in at $740/kWh, including all related system components including inverter for AC-coupling. This puts the RFB offering in about the same price range as the comparable quotes for Li-ion and PbA systems as shown in Figure 4. Indicative quotes for sodium sulphur ($330/kWh), sodium ion ($400/kWh), zinc air ($250/kWh) and nickel iron ($500/kWh) should be treated with caution at this stage, since fully installed systems of these technologies were not realised.

<u>Recent cost reductions</u>

As with current capital costs, a variety of responses were given on the degree to which battery costs had reduced over recent years, but with two unifying themes: namely that 1. Li-ion battery costs have fallen significantly, but that 2. PbA battery costs have been somewhat more stable.

As an example, one respondent reported a Li-ion battery pack cost reduction of 21% over the last two years, whilst another reported about 16% per year over recent years. Countering this, one respondent reported that costs from their supplier had not fallen in 5 years and they were now looking to change supplier. Two respondents outlined their belief that Li-ion batteries would reach an approximate $250/kWh level in the near future, although one of these respondents believed the cost would not fall significantly below this. Another respondent stated that they believed Li-ion capital costs would converge with PbA costs in the near future.

Where cost reductions were reported in PbA batteries, these were put down to increasing volumes ordered from suppliers, or from achieving lower costs through greater competition from suppliers.

3.3 Performance of technologies

In this section, we present a range of insights arising from our series of interviews on on-the-ground experience of electricity storage technologies, and how these compare to stakeholders' expectations and manufacturers' specifications. These are divided into a number of categories in the subsections below and chiefly refer to lithium-ion and lead-acid batteries, as these are the most used amongst companies represented by our interviewees (see Figure 5). However, these are broken down by technology variant where relevant, chiefly between cathode chemistries for lithium ion batteries and between sealed (sometimes referred to as valve regulated) and flooded for lead-acid. In some cases, reference is made to other less mature technologies: vanadium redox-flow and saltwater based. One interviewee also made use of a hybrid lithium-ion/lead acid technology.

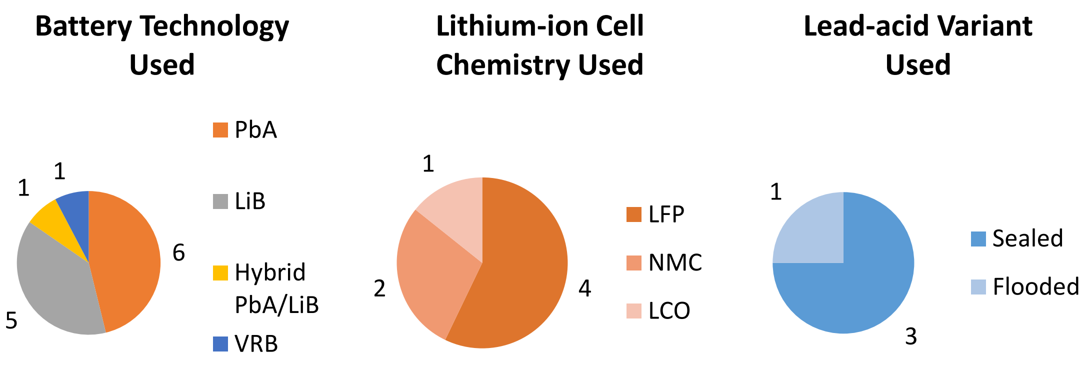


Figure 5 – Number of companies using each of a range of storage technologies (of eight companies employing battery storage technologies)

A summary of quantitative technical parameters, where interviewees had sufficient experience to provide these, is provided in Table 2.

Table 2 – Summary of quantitative technical parameters for battery technologies.

System	LiB (LFP)	LiB (LFP)	PbA (sealed)	PbA (sealed)	PbA (sealed)	PbA (flooded/sealed)	LiB/PbA Hybrid
Efficiency	95-98%	"No issues"			80 - 85%	75-80%	~92%
Cycle Life	~2500	Aim for min. 800	~1000	~500	~2500	~2800 (spec sheet)	~2500
Depth of Discharge	90% limit	80% limit	25% typical, 50% limit	40% typical, 50% limit	20% typical	60% limit (50% in practice to extend life)	
Shelf Life			~1yr, recharge after 6 months	~1yr, recharge after 6 months	~1yr, recharge after 3-6 months		
Operating Temp Range	0 to 55°C (C rate temp. dependent)	0 to 50/55°C	Most units 20 to 30°C. Accelerated degradation at 45°C.	Most units 20 to 30°C. Accelerated degradation at 45°C.	-15 to 55°C (C rate temp. dependent)		-15 to 55°C (C rate temp. dependent)

Ease of installation and use (including size and weight) Interviewees reported no issues with installation for lithium-ion batteries, but five of six using lead-acid batteries indicated that size and weight were an issue. This was an issue both in terms of transport to remote areas and manoeuvring and installing in a position with sufficient space upon delivery, and was particularly challenging for mobile agricultural applications. One respondent indicated that flooded and sealed lead-acid batteries each come with their own issues in terms of installation. A flooded lead-acid battery does not require multiple stacks, while stacking of sealed lead-acid batteries for larger mini-grid systems (tens of kWh) requires much physical effort to lift and connect different modules. However, flooded lead-acid batteries can only be installed upright, need air ventilation, and cannot be in the same room as electronics, meaning that the storage system as a whole requires two rooms.

Charge and discharge characteristics (power, length of charge / discharge) Technologies broadly performed as interviewees expected in terms of charge/discharge characteristics. However, one interviewee indicated that current flow is an issue in lead-acid batteries and that these batteries cannot be charged as fast as they would like. The requirement of a long period of slow charging to minimise degradation in lead-acid batteries was a motivating factor for one interviewee's company to develop a hybrid lead-acid/lithium-ion solution, in which the lithium-ion battery can be used to absorb charge above the optimal rate for the lead-acid battery in the system

Efficiency Most respondents indicated that they are satisfied with round-trip efficiencies of battery technologies and report values of above 90% for lithium-ion, and 75-85% for lead-acid batteries.

Cycle life Clear definition of cycle life was challenging as, owing to the relatively recent expansion of rural electrification systems making use of electric batteries, many interviewees had only worked with systems which had not reached, or were just beginning to reach the end of their useful lives. This was especially the case with companies using lithium-ion batteries, many of whom had switched recently. However, those who had more experience provided some useful insights into the dependence of cycle life upon operating conditions, how the battery is used, and in some cases manufacturer.

- **Operating conditions** Operating at higher temperatures than those in which battery cells were developed was identified as an important factor in determining cycle life by one company making use of only lead-acid batteries, one making use of only lithium-ion batteries, and one making use of both. One interviewee shared a rule of thumb that lifetime typically decreases by approximately 50% for every ten degrees above lab temperature across battery technologies (see section on thermal management).

- **Battery Usage Characteristics** Interviewees using lead-acid batteries indicated that depth-of-discharge was a crucial factor in determining cycle life (see Table 3). One interviewee indicated that to minimise degradation in lead-acid batteries, they should be charged slowly and kept as close to fully charged as possible. Interviewees found depth-of-discharge to have less of an impact on lithium-ion batteries (two interviewees ran these batteries to 90% and two to 80% depth-of-discharge), but one interviewee indicated that high C rates in lithium-ion batteries accelerate degradation, motivating the use of a hybrid system with lead-acid to keep C-rates down[2].

Table 3 – Cycle life for lead-acid batteries with a range of discharge characteristics reported by interviewees

DoD Limit	80	unspecified	unspecified	unspecified	60
Typical DoD (%)	50	50	40	25	50
Cycle Life	500	500	850	1000	2800 (spec sheet)

- **Manufacturer** Some interviewees indicated significant differences between performance of battery technologies by manufacturer. This was particularly the case with lithium-ion batteries, where the manufacturing sector is relatively immature and there are more players active than for lead-acid, where the market has consolidated into a smaller number of reputable companies. One interviewee divided lithium-ion cell manufacturers into three tiers. A bottom tier which are low in cost and they had been using up to now, but gave relatively low cycle life, a middle tier in which there is a wide range of performance and it is hard to know what is good or bad, and a top tier high quality electric vehicle cells, which perform very well, but do not come in readymade packs. Amongst the middle tier, the interviewee found that performance does not correlate well with cost.
  This is in line with findings of another interviewee who had tested lithium cells from around 15 suppliers over 6 years who had identified differences of order 20% between suppliers specified lifetime and realised lifetimes, which did not always correlate with cost, though the cheapest tended to perform poorly.

Shelf life Shelf life varies by technology and condition in which the battery is kept. Two suppliers of lead-acid batteries indicated that batteries should be kept fully charged, and charged back to full if stored for more than six months. One supplier indicated a maximum storage time of one year, and both indicated that they kept batteries stored for as short a period as possible. Lithium-ion batteries tend to have a higher shelf life, and one interviewee indicated a shelf life of two years. However, they indicated that these batteries should be kept at an intermediate state of charge, and that lifetime was dependent on storage temperature – which should not exceed 45°C. One interviewee noted issues with customers keeping lithium-ion batteries fully charged for long periods (based on their experience with lead-acid), which causes accelerated battery degradation, and indicated better customer education could help to prevent this.

Durability to local temperature and environmental conditions As noted previously, high temperatures can have a large impact on battery cycle life. One interviewee also indicated efficiencies of lead-acid batteries reduced from 85% specified by manufacturers to 75-80% at temperatures at around 45°C.

Operating temperature range/thermal management No interviewee had a system to directly cool the battery, and none were looking to add this due to prohibitively high

[2] In such hybrid systems, the lithium-ion battery is usually favourably charged and discharged, with the lead-acid battery used only when the lithium-ion battery reaches a minimum charge threshold. However, both may be used to provide current when high currents are required, reducing the strain on both batteries.

associated cost. Two interviewees mentioned other components in the system were cooled (inverter and electronics) and three indicated that rates of charge/discharge are reduced as temperatures approach 45°C, and the system is shut off at temperatures above this level. Only one interviewee using lead-acid batteries indicated that they do not use thermal management (Figure 6).

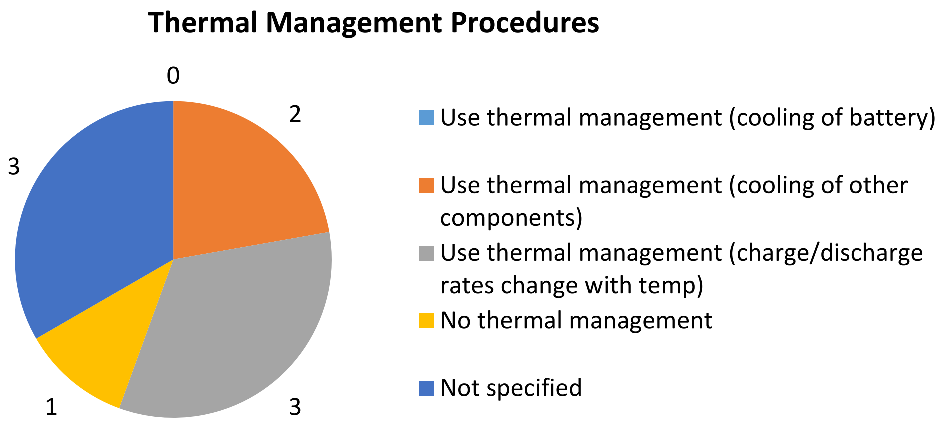


Figure 6 – Thermal Management Procedures

Reliability Most interviewees did not specify significant issues with reliability. One supplier making use of lead-acid batteries indicated that they typically find either very sudden, abrupt, failures or slow degradation with 1-2% fail within first 2 months. One interviewee making using of lithium-ion batteries (LFP) indicated that their previous manufacturer provided an additional 10% of batteries to account for failures, but that failure rates were in some cases higher. This interviewee had recently moved to a manufacturer providing more reliable products.

Flexibility (e.g. Ease of expansion to larger loads) In general, expansion of a system appeared to be challenging. One interviewee's company oversized systems, only allowing customers access to a certain amount of energy dependent on tariff (justified in part by more rapid degradation of the lead-acid battery at higher usage rates). Two others providing solar home systems sought to upgrade customers to larger systems after a period of usage. One interviewee indicated that expansion of energy capacity is relatively simple and can be achieved simply by installing additional batteries. However, expansion to a larger power requirement is more challenging, requiring a larger battery and additional electronics (charge controllers for DC off-grid/mini-grid, and inverters for larger AC applications).

Safety Interviewees were largely reluctant to talk explicitly about safety issues they had experienced, but indicated that this is a crucial concern, both due to the direct consequences of a safety issue, and the reputational damage associated with such an issue.

The three companies specifying no safety issues all made exclusive use of lead-acid technologies. However, one interviewee also mentioned safety as a reason for choosing lithium-ion over lead-acid, and another experienced more safety issues with lead-acid than lithium-ion batteries, and two interviewees indicated that issues can occur with production of hydrogen gas if lead-acid batteries are charged too quickly, which can lead to explosions without sufficient ventilation.

Safety issues associated with thermal runaway in lithium-ion batteries, potentially leading to fires and explosions, were mentioned by two interviewees. However, one indicated that this is highly chemistry dependent and is much more of an issue with higher voltage (3.6V), higher energy density NMC cells than LFP cells commonly used in rural electrification (3.2V), which were described as tolerating a lot of abuse (rapid charge/discharge cycles and penetration with a nail in a controlled environment) without causing major safety issues. The same respondent indicated that this was a key reason for using LFP rather than NMC batteries in their systems.

Performance degradation Interviewees using both PbA and LiB noticed degradation over the lifetime of their project, with one interviewee using lithium-ion batteries indicating that customers also notice degradation in capacity over the lifetime of the product. In most cases degradation over the useful lifetime of the battery is relatively minor, and remote monitoring allows replacement of products before performance drops too low.

Maintenance requirements Minimal requirements were identified for lithium-ion batteries – projected to be approximately once per 60 months (NMC). Maintenance requirements for sealed lead-acid batteries are minimal (once per 18-24 months approximately), although one interviewee indicated that wear on connectors could be an issue. Flooded lead-acid batteries must be refilled periodically with water, and one interviewee indicated a preference for use of sealed rather than flooded lead-acid batteries due to this reduced maintenance requirement. One interviewee indicated that a key area of maintenance in PV systems working with lead-acid batteries is proper cleaning of the solar PV panel. Dust covering PV panels in certain regions can drastically reduce their electrical output, meaning that lead-acid batteries discharge as they are used, but are never able to fully recharge, resulting in long periods of low charge which the interviewee stated can cause catastrophic failure of these batteries within six months. Lithium-ion batteries are more tolerant of low levels of charge, so this is not such a major issue for this technology.

How does the performance compare to the claimed / boilerplate performance? Interviewees using both lead-acid and lithium-ion technologies had varied experiences in terms of how product specifications related to actual performance (See Figure 7), particularly regarding cycle life, as discussed in earlier sections. Some interviewees indicated mixed experience with suppliers, with some performing as, or better than, specified, and others worse. In some cases, it is unclear whether practitioners' expectations are based on product specifications or more general knowledge of the operating characteristics of the technology. One interviewee who had tested lithium cells from a range of suppliers from around 15 suppliers over 6 years who had identified differences of order 20% between suppliers specified lifetime and realised lifetimes, which did not always correlate with cost, though the cheapest tended to perform poorly, and worse performers perform generally worse than their own spec and worse than competitors. This interviewee also indicated that the same battery chemistry from different suppliers tends to have similar specified performance, but realised performance differs. The same interviewee indicated that battery technologies in off-grid applications are typically being used in a different application from that for which they were designed and tested, with challenging operating conditions (often rapid and variable charge and discharge at a range of temperatures), so differences from manufacturers' specification sheets are not surprising.

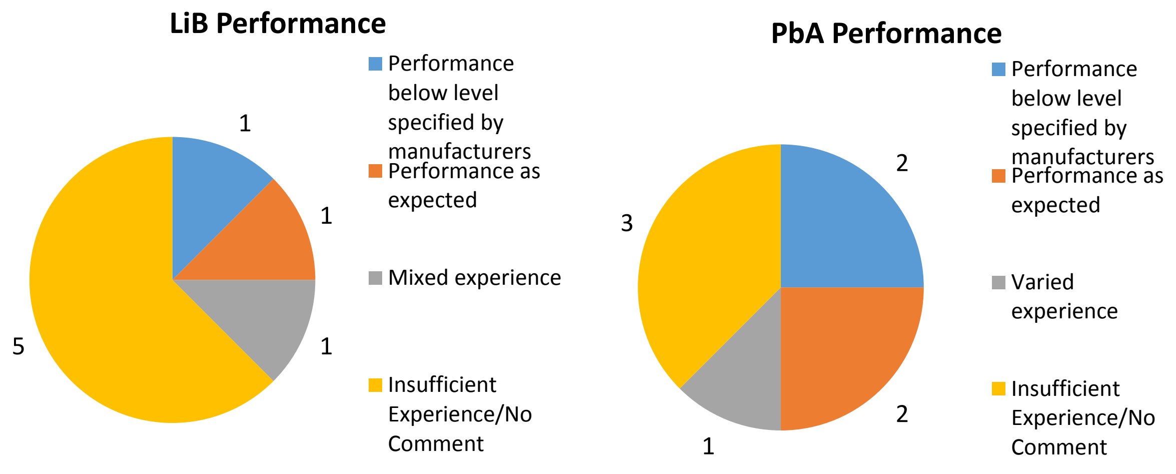


Figure 7 – Specifications relationship to actual performance

Is it clear how to operate these technologies so as to maximise performance, reliability, lifetime (e.g. from supplier user guides and information)? Broadly, interviewees were happy with the level of instruction provided by suppliers. However, one user each of lithium-ion and lead-acid batteries indicated that they are still working out how to maximise performance and two had large amounts of data on historical performance of battery technologies in the field which they had yet to fully analyse. Two interviewees explicitly indicated that there is a role for academia to analyse and disseminate information in this regard.

Awareness of performance trajectory of storage technologies Interviewees using lead-acid batteries indicated that the technology is mature, and they are not seeing improvements. These interviewees are keeping a close eye on falling costs and improving performance of lithium-ion batteries to determine when to switch. One interviewee using lithium-ion batteries indicated that they are seeing an improved lifetime for cells of similar cost, with implications for reliability and lifetime cost, which the interviewee valued more highly than capital cost. Another interviewee using lithium-ion batteries indicated that cycle life and safety were largely dependent on chemistry and they were not seeing improvements in this regard but were seeing improvements in energy density (albeit in some cases, at the cost of reduced safety).

3.4 Value Chain and Full Lifecycle

Interviews have shown 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 lithium-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 mini-finance or operate on a 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, albeit difficulties 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 if lead-acid or lithium-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 lead-acid and lithium-ion batteries. Other manufacturers are based in Bangladesh or South East Asia (Thailand, Malaysia). Regarding lithium-ion batteries, China is skew to LFP-type. NMC-type batteries tend to come from East Asia (South Korea, Japan).

Due to lack of transparency around device performance, the right choice for supplier is perceived as a key difficulty. In addition, there is not always a direct correlation between technology performance and cost with higher priced systems performing worse than and low-cost. One interviewee categorised suppliers in three categories:

1. Top: High performance battery cells, but no integrated battery pack products
2. Middle: Mixed quality products; challenging to know which batteries perform good or bad
3. Bottom: High failure rates; 10% extra batteries provided as warranty, but often higher proportion fails

The batteries are sea-shipped to the target market, which takes 6 to 8 weeks for East Africa. Batteries cannot be air-shipped due to safety concerns (lithium-ion) or weight (lead-acid) and must be at around 30% (lithium-ion) or 100% (lead-acid) state-of-charge during shipment to avoid degradation. Trucks transport the batteries from any harbour to a central warehouse and smaller vans continue to the shops in the target market. Last mile distribution is usually done via door-to-door sales agents. While most lead-acid batteries are refurbished and re-sold informally, lithium-ion systems are dumped in landfills. Some companies are now starting to specialise in shipping used batteries to Belgium (lithium-ion) or India (lead-acid) for recycling.

No particular issues in terms of availability or supply chain constraints for solar home systems were identified. The key enabler of the market is the telecommunication infrastructure and mobile phone penetration, enabling safe and regular payments through mobile money, easy communication with customers and monitoring of the devices. In addition, the lack of VAT on energy products in East Africa supports growth.

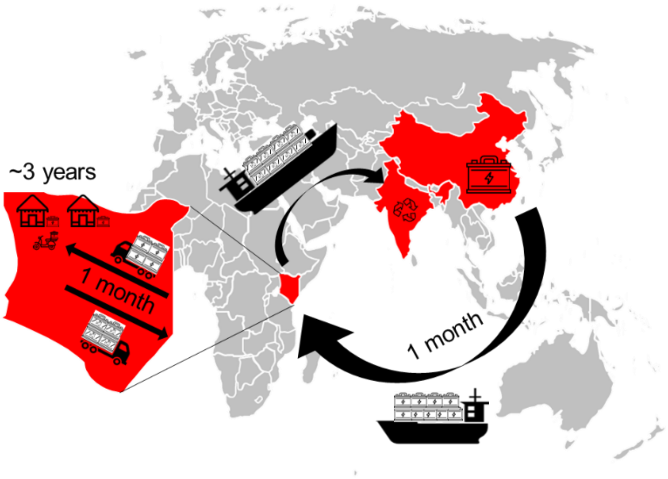


Figure 8 – Sample supply chain for a solar home system technology provider in Kenya using lead-acid batteries. The batteries are manufactured in China and shipped to Mombasa, Kenya, from where they reach the shop via truck. Door-to-door delivery time is between 6-8 weeks. Last mile delivery to customer 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.

The situation is no different for **productive use products.** The vast majority of lithium-ion and lead-acid batteries are sourced from South China, only with NMC-type lithium-ion more likely to come from East Asia. Wholesalers and retailers from East Africa or India exist, but are more expensive. There is no shortage of suppliers of any technology. A bottleneck for productive use products is the availability of battery management systems (BMS) for their higher voltage technology. At the moment, significant demand exists for lower power solutions like solar home systems.

Storage technology value chains for **nanogrids** or **minigrids** are more diverse due to higher customisation of systems. Where standard systems are still applicable, they will again be sourced from South China or India (domestic customer). Larger, capital-intensive systems will see close collaboration between manufacturer and installer on business case and performance specifications, which favours larger, internationally diversified manufacturers (Panasonic, SMA, Trojan, Samsung, GNB Exide). This is because of long lead time for those projects (12-24 months) and fully packaged solutions with suitable warranties that are offered. Shorter lead-times are highly desired by the industry. In terms of technology providers, most exist for small to mid-scale range lead-acid, but are increasingly chased by lithium-ion. There are a few providers for flywheels, less for redox-flow batteries and fewest for metal-air or sodium-ion. The market segmentation shows that 90% of minigrid storage capacity is lead-acid. One bottleneck is the availability of AC-containerised solutions. Most suppliers only deliver the core technology, i.e. battery packs, but system integration has to be done individually. The exception are established system integrators that are expensive (ABB, Siemens). Individual system integration may lead to problems in battery / inverter / BMS interaction. Thus, a solution is to purchase the core technology separately and commission a system integrator with the full AC-containerised solution (Quinos, Cenekon).

Another advantage of shipping full containerised solutions is that less import tax applies than shipping all components separately.

While most companies could not identify government-specific regulations or policies favouring or hindering certain technologies, some highlighted high import duties and costly certificates required for lithium-ion battery imports. The VAT free import of energy products overall supports the energy access business in most countries. Lead-acid batteries might be favoured in some regions due to their incumbency and the resulting lobby and skill availability. A barrier for hybrid battery solutions is that project tenders often specify one technology.

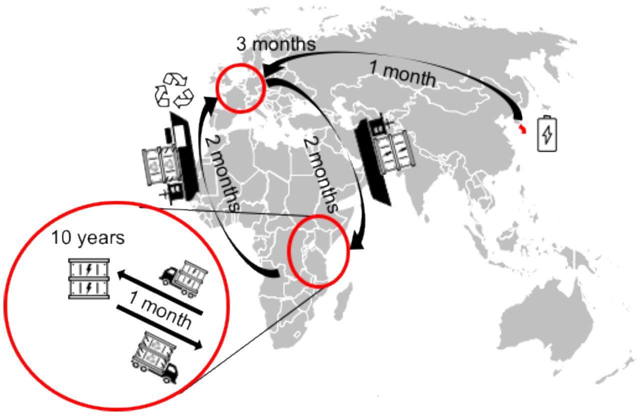


Figure 9 – Sample supply chain for a minigrid supplier for rural electrification in East Africa with a lithium-ion battery. The lithium-ion cells are shipped from South Korea to Europe where they are assembled to a containerised AC solution. The system is then shipped to East Africa, where it needs to 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 Europe for recycling. In many cases, lithium-ion batteries are currently dumped on landfills.

<u>What are the procedures for disposing of the technology at its life end?</u>

End of life procedures vary between interviewed companies (Figure 10), with some returning to manufacturers, some contracting recycling companies to perform this service, and others providing no details or with no end-of-life procedure established. In most cases, there were no major external drivers to become more environmentally responsible, and efforts which were being made in this regard were largely tied to companies' ethos and/or concern for their reputation.

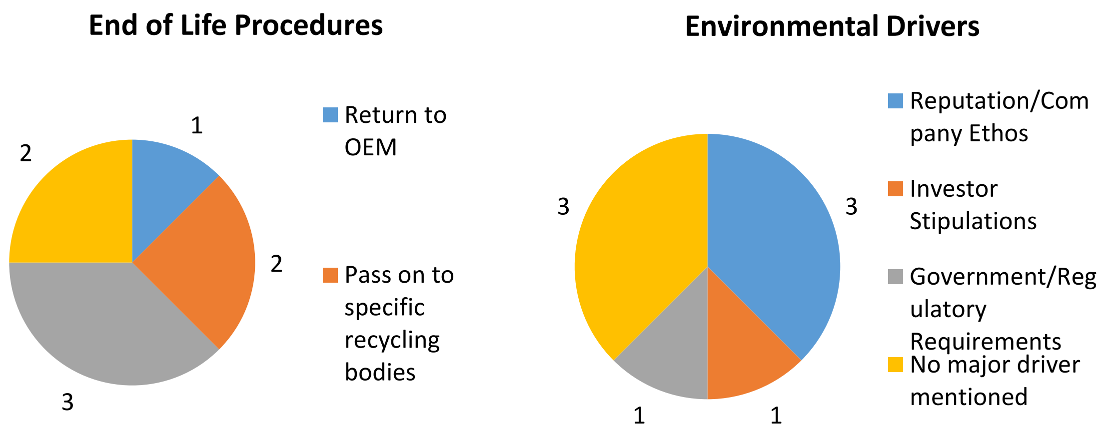


Figure 10 – End of life procedures and drivers for companies to adopt environmentally friendly practices

How easy and commercially viable is it to recycle, refurbish/ reuse/ repurpose?

Lead-acid batteries are relatively straightforward to recycle but can have significant health impacts associated with informal recycling. Without proper safety equipment, fumes can spread to local communities resulting in widespread lead poisoning. Additionally, there is only one effluent treatment facility in East Africa, and dumping of concentrated sulphuric acid prior to recycling of the lead component of such batteries is widespread.

There remains no established protocol for recycling lithium-ion batteries, and the cost of recycling is currently too high relative to the value of materials contained to make this economically viable, in part due to the large number of components in the lithium-ion battery cell, and partly due to differences in chemistry between batteries. This has been identified as an issue which goes beyond the solar home sector (e.g. mobile phones, which represent a much larger waste stream, not large enough to make recycling economically viable). However, lithium-ion batteries are classified as harmful, rather than toxic, and at present do not present a toxicity risk on the same scale as that of lead-acid batteries. Risk of fire or explosion in used lithium-ion batteries represents a larger concern.

Printed circuit boards also contain toxic materials, but recycling in Europe is economically viable provided the products can be obtained from users at end of life.

What organisations, regulations and procedures are in place to help disposal and recyclability, who owns overall responsibility?

Interviewees indicated that, at present, nobody owns responsibility for safe disposal of electrification systems at the end of their life. Whilst there are often regulations in place stipulating that environmental waste should be disposed of safely, this regulation is often vague and ineffective in practice. However, one respondent outlined a number of organisations/governmental departments available to provide support in Tanzania specifically:

- Vice President's division of environment.
- National environmental council for environmental impact assessment.
- Ministry of industry and trade (governs local businesses and industries, not focused on environment specifically).
- Responsible lead smelters Gaia eco-solutions and OK Platt.

Additionally, the WEEE Centre and Phenix recycling represent commercial enterprises facilitating responsible disposal of lead-acid batteries and e-waste.

What are the ecosystem gaps that exist to make the recycling feasible in the relevant markets?

Respondents identified two key ecosystem gaps to make recycling feasible:

- Detailed regulation on e-waste.
- More reputable and responsible and safe recycling companies (Phenix recycling and the WEEE centre were cited as current examples of best practice).

One respondent in particular noted that in certain regions of Africa this could be very hard to achieve, owing to the politicised nature of lead-acid batteries, and the influence of a large number of (largely unregulated) informal lead-acid battery recycling companies.

What is best practice in these areas, considering other geographies/ markets?

Most interviewed companies did not have a view as to current best practice with regards to environmental impact. However, those that did cited Phenix Recycling and the WEEE centre as examples of best practice, whose operations are broadly similar:

- Collect e-waste (at a specified cost per kg) and lead-acid batteries (for free, not classified as e-waste) from customers and deliver to dismantling centre.
- Deliver lead-acid batteries to recycling facilities with high environmental standards
- Dismantle e-waste, and transport those components which cannot be recycled in country abroad, including lithium-ion batteries, for which there is at present only one recycling facility (Umicore in Belgium)

One stakeholder strongly indicated that best practice with much e-waste is to export from countries of use at present, as existing recycling facilities outside of the region currently operate at under capacity and need additional volume.

3.5 Cold storage

Overview

The key applications cold storage companies are focussing on at the moment is agriculture and health. While in in developing countries up to 45% of farmed food (milk, meat, crops) is wasted due to lack of cooling, the health sector is appealing due to the high value products that must be stored cool (i.e. vaccines, blood bags). Other potentially interesting sectors are refrigeration and air-conditioning for domestic or retail purposes and the usage of excess renewable energy.

Thermal energy can be provided from a storage reservoir directly or indirectly depending on the storage concept. Thermal storage refers to the heat/cold stored in materials, for example ice cubes that can be used directly to provide 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.

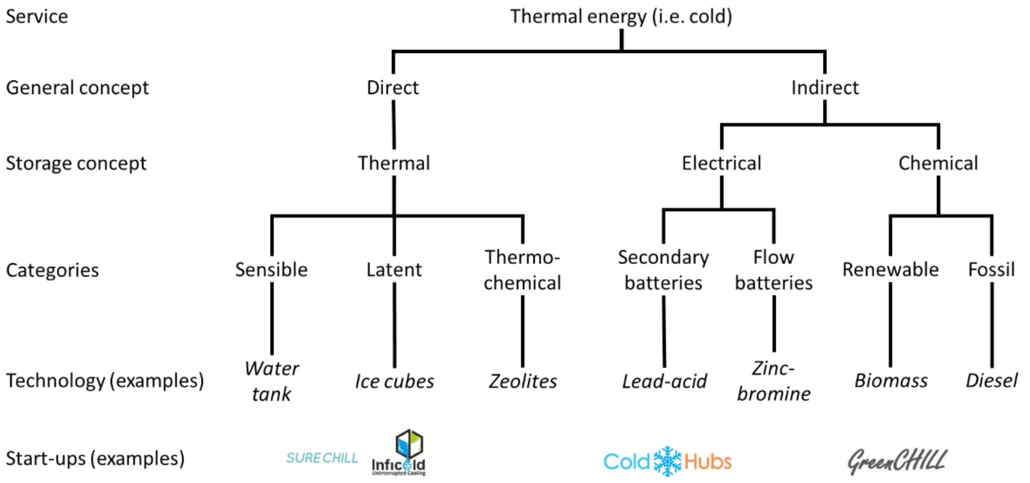


Figure 11 – Different technology pathways to providing thermal energy. Sample technologies are in italics, sample start-ups are represented by their logo.

The three direct thermal energy storage categories are[5]:

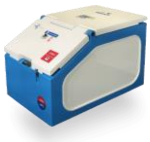
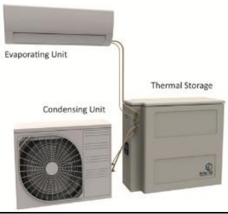
- Sensible - Heating/Cooling of material without changing its phase
- Latent - Heating/Cooling of phase-change materials; latent heat - transition from one state to another (gas-fluid; fluid-solid)
- Thermo-chemical - Chemical reactions that release/ consume heat

The key components of a thermal energy storage system are the material, which absorbs thermal energy by changing its characteristics and energy transmission components like heat exchanger, heat transfer fluid, energy conversion device, storage container and ancillary components (pumps, valves, pipes, etc.).

An important concept to categorise thermal storage applications for cooling is the cold chain:

1. Cooling at production source
2. Cooling during transport
3. Cooling at retail / consumption stage

Product Examples

Product	Specifications	Principle
Sure Chill www.surechill.com 	**Principle**: Sensible + Latent **Material**: Water **Target Temp.**: 4˚C **Duration**: ~10 days **Cooling capacity**: **Relative humidity**:	Natural water circulation due to water being heaviest at 4˚C • On: Ice-formation on top • Off: 4˚C melt water sinking to cool products; warmer, used water rising to melt ice
Inficold www.inficold.com 	**Principle**: Latent **Material**: "low cost energy-dense phase change material such as ice" **Target Temp.**: -20 - 20˚C **Duration**: ~18 hours **Cooling capacity**: 1-30 tons **Relative humidity**:	Thermal phase-change storage device integrated with conventional refrigerators, solar coolers, ACs • On: Power used to cool phase-change material • Off: Thermal energy provided through phase-change material drives conventional cooling cycle
Easterner http://www.evaptainers.com 	**Principle**: Latent **Material**: Water (1 litre per day) **Target Temp.**: 15-20˚C below ambient **Duration**: up to 2 weeks **Cooling capacity**: 60 litres **Relative humidity**:	Air can only hold a certain amount of water subject to its temperature and pressure. As a result water of wet surfaces tends to evaporate (e.g. air drying laundry). However, the water of the wet surface needs to draw heat from a source to evaporate, i.e. transfer from fluid to gaseous phase, which triggers *evaporative cooling*.
Tessol https://www.tessol.in 	**Principle**: Latent **Material**: Phase-change material **Target Temp.**: -25-18˚C **Duration**: ~18 hours **Cooling capacity**: 1-20 tons **Relative humidity**:	A eutectic material composition acts as phase-change material for cooling. • On: Power used to cool eutectic PCM • Off: Thermal energy provided through PCM
Coldhubs (via batteries) www.coldhubs.com 	**Principle**: Sensible + Electrical **Material**: 120mm insulating cold room panels, "high capacity batteries" **Target Temp.**: **Duration**: depends on storage and battery size **Cooling capacity**: **Relative humidity**:	Solar-powered cold stations for 24/7 storage and preservation • On: Energy from solar panels mounted on the roof-top of the cold room are stored in high capacity batteries • Off: These batteries feed an inverter which in turn feeds the refrigerating unit
Green Chill (via biomass) http://www.newleafdynamic.com 	**Principle**: Sensible + Biomass **Fuel**: Cow-dung cakes, biogas, biomass pellets, dead wood, producer gas, farm waste **Target Temp.**: -5-20˚C **Duration**: 3-4 hours (w/o fuel) **Cooling capacity**: 10-15 tons **Relative humidity**: 20-90%	Waste-powered cold stations off-grid bulk milk coolers and cold storage • On: Biomass waste or waste heat used to drive cold storage unit

4. What storage technology is best suited to which application?

The most suitable storage technology will vary with both application and business model. It is not possible to be entirely prescriptive owing to variations in exact requirements (such as charge / discharge requirements, reliability, size and cost requirements) as well as environmental conditions for different energy access applications, and exactly how different technologies will perform in such settings.

Storage technologies used in the different energy access applications provided by interviewees in this study (chiefly lead-acid, lithium-ion, and in one case redox flow batteries) are broadly in line with those which we would expect to be most suitable for those applications from an academic perspective [6–9]. Each of these technologies is able to operate at a range of scales and provide a good balance of energy capacity and power output with reasonable levels of affordability.

According to the information provided by interviewees, appropriate storage technologies for different applications are as follows:

- For low power, low energy **picosolar** products, lithium-ion batteries are an appropriate choice owing to their lightweight, relatively high cycle life, and affordability.
- In **solar home systems**, both lead-acid and lithium-ion are viable. Where high power or rapid cycling are required, and in business models where rapid payback is not required, lithium-ion batteries are likely to be favourable. Where capital cost is a significant constraint, lead-acid batteries may be more favourable at present, but the improving economics of lithium ion batteries could change this picture in the next few years.
- For systems of **nanogrid** size and above (or solar home systems offering higher levels of energy access than those considered in this study), hybrid lead-acid/lithium-ion battery systems may be favourable, offering lower costs than pure lithium-ion systems, but with higher lifetimes than lead-acid systems. However, the added cost and complexity of battery management for such systems are likely prohibitive for smaller applications at present.
- Considering **higher capacity and higher power systems**, lithium-ion batteries may be favourable for applications with high power requirements for short periods of time (e.g. backup for generators in mining operations), whilst redox-flow batteries may be more suitable for larger systems where power is required for longer periods of time (hours).
- For **agricultural and commercial cooling**, direct storing of cold energy could well be more efficient and cost-effective than storage in electrochemical batteries, although direct thermal storage technologies have been deployed in relatively few sites so far.

In general, these views on the appropriateness of different storage technologies for different applications are in line with what the literature indicates, given the differential cost and performance characteristics of these technologies.

5. How could practice around technology choice be improved?

A number of recommendations for practice around technology choice, either at an individual company or at a system level, emerge from this research, as summarised below:

- **Improve consistency of storage product quality -** A recurring theme amongst interviewed participants was variability in battery performance between suppliers, and challenges in ensuring consistency of quality. Efforts to establish an independent set of standards, similar to that which exists for off-grid lighting appliances [10], should be supported in order to improve these. Additionally, the grouping together of smaller suppliers of energy access products to increase purchasing power could be beneficial in terms of ensuring good value is obtained from battery suppliers.

- **Better integration of peripheral components for energy access applications -** A number of interviewees indicated that, whilst they were able to source energy storage technologies which could meet their system needs, they had difficulty in sourcing peripheral components, such as battery management systems, sometimes having to design and build these themselves at significant expense. A greater availability of "off-the-shelf" solutions matched to different battery technologies in a variety of configurations could help to reduce this expenditure and simplify system design.

- **Ensure responsibility is taken for the whole product supply chain and design for reusability/recyclability -** A range of materials required for lithium-ion batteries (lithium, cobalt, graphite, nickel) are largely sourced from regions of political instability [11], and in some cases associated with systematic human rights violations and environmental negligence [12]. Effective and safe recycling procedures exist for lead-acid batteries in Europe and the US, where more than 95 per cent of lead-acid batteries are recycled at the end of their lives. However, a high incidence of lead poisoning in regions of the developing world has been attributed to widespread informal recycling without proper safety equipment [13–15]. The World Health Organisation (WHO) estimates that each year lead poisoning contributes to 600,000 new cases of children developing intellectual developmental disorders, and accounts for 143,000 deaths [16], partly attributed to informal lead-acid battery recycling. Lithium-ion batteries could also be hazardous without proper recycling at the end of their useful lives [17,18], and recycling procedures are not well established and are more challenging than for lead-acid batteries, owing to a more complex design and a wider range of materials used in their construction [19]. As such, it is paramount that energy access companies design in reusability/recyclability (for example, through modular design and avoidance of unnecessary use of adhesives) [19], and take responsibility for the entire supply chain associated with their products, from raw material extraction to end-of-life whilst taking into account priorities and economic significance of existing formal and informal repair networks [20]. Effective regulation in order to bring this about represents an important system-level gap.

6. How will the most relevant technologies vary over the coming years?

Continued reductions in costs in lithium-ion batteries [21,22] are expected to drive increasing competition with lead-acid batteries over the coming years. This means that lithium-ion batteries are expected to become dominant in solar home systems in the next 5 – 15 years. Cost reductions in NMC based lithium-ion batteries for EV applications may make them more competitive relative to LFP batteries over a similar time period.

Hybrid lead-acid/lithium ion systems for larger systems may grow in their usage and continue to represent the most viable option for nano/minigrid systems. Other battery systems in early commercialisation or R&D phases, such as sodium-ion or flow batteries, may come to play a significant role further in the future if they are able to compete on cost terms. Sodium’s greater abundance compared to lithium mean this is conceivable [22–24], whilst the scalability of flow batteries, and the relative simplicity of their design, mean that these could also provide economically competitive in the future. However, owing to long time periods associated with both R&D breakthroughs and going from first commercial products to widespread usage, this is unlikely to occur within the next decade, given that there is inherent risk in sourcing new battery chemistries to provide a reliable, field-tested product.

The off-grid sector is largely reactive in terms of technology choices, and without a significant increase in its scale and/or its bargaining power, it is likely to have to adopt technologies developed for other applications, rather than having technologies developed specifically for this sector.

Whether the energy access sector could grow to a level at which the development of storage technologies specifically for this application would be viable remains an open question.

7. Discussion and Policy Recommendations

With over 1 billion people lacking access to electricity, and continued reductions in cost of PV panels and Li-ion batteries, the rural electrification industry may be expected to continue its rapid growth for some years to come.

As 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 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.

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. Current best practice is to collect e-waste and ship it to countries with safe and effective recycling centres, many of which are running at under-capacity. However, this issue is not confined to the rural electrification sector and is likely to be extremely challenging in some regions owing to the lucrative nature of informal recycling, and powerful and established stakeholders working in this sector.

Appendix: Overview of Technologies and Characteristics

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.

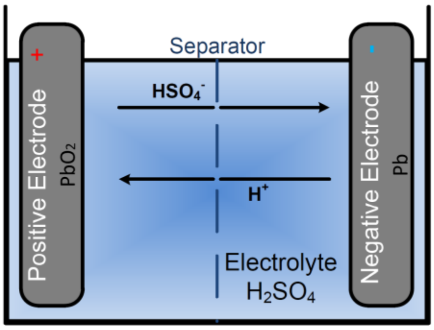


Figure A.1 - Principle of the discharge and charge process in a Lead-acid cell [25]

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[26].

- <u>LCO/Gr Lithium ion cells</u> 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.

- <u>NMC/Gr Lithium ion cells</u> 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.

- <u>LFP/Gr Lithium ion cells</u> 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).
- <u>LFP/LTO Lithium ion cells</u> 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.

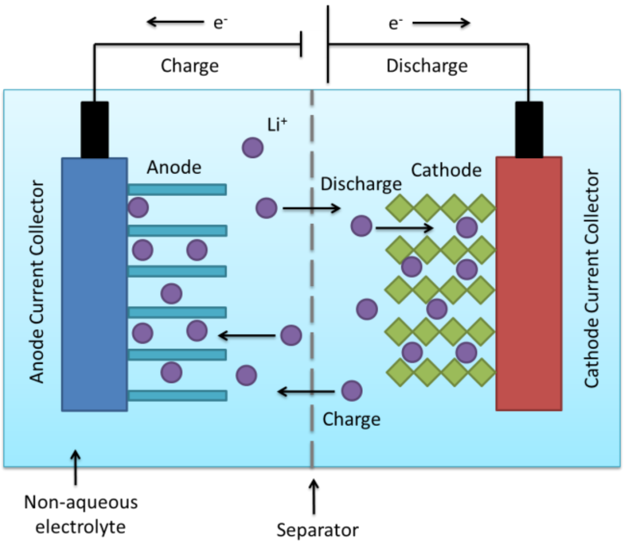
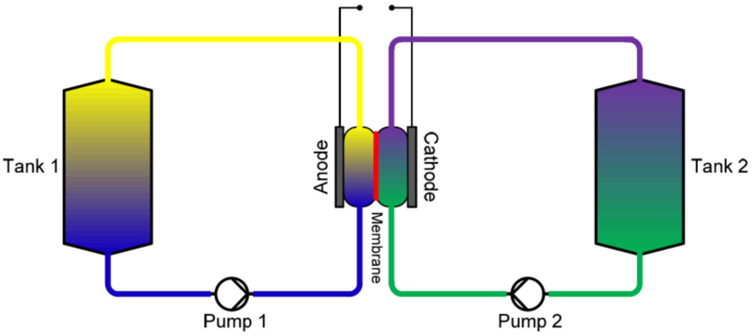


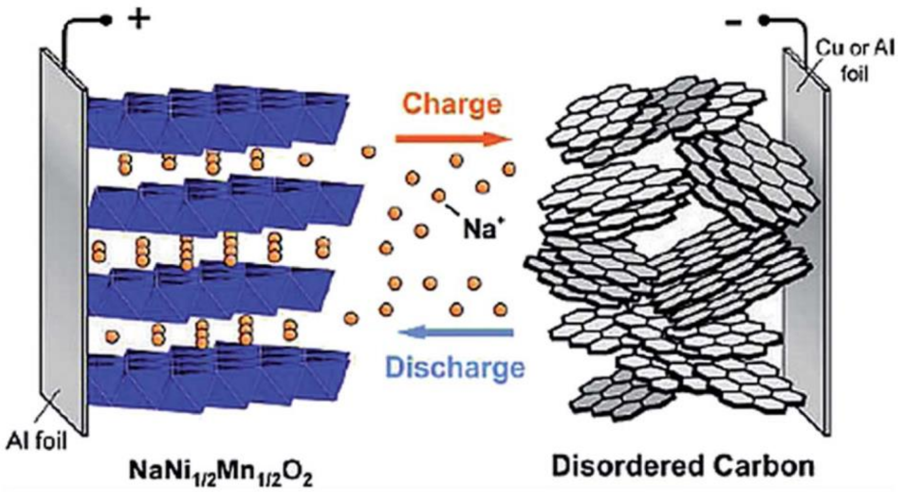
Figure A.2 - Schematic intercalation and de-intercalation of lithium in anode / cathode of a lithium-ion battery cell [22]

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.



FigureA.3 – Schematic design of a redox-flow battery [25]

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[27]. 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.



FigureA.4 - Schematic of sodium ion batteries with a layered transition metal oxide cathode and carbonaceous anode [28]

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.

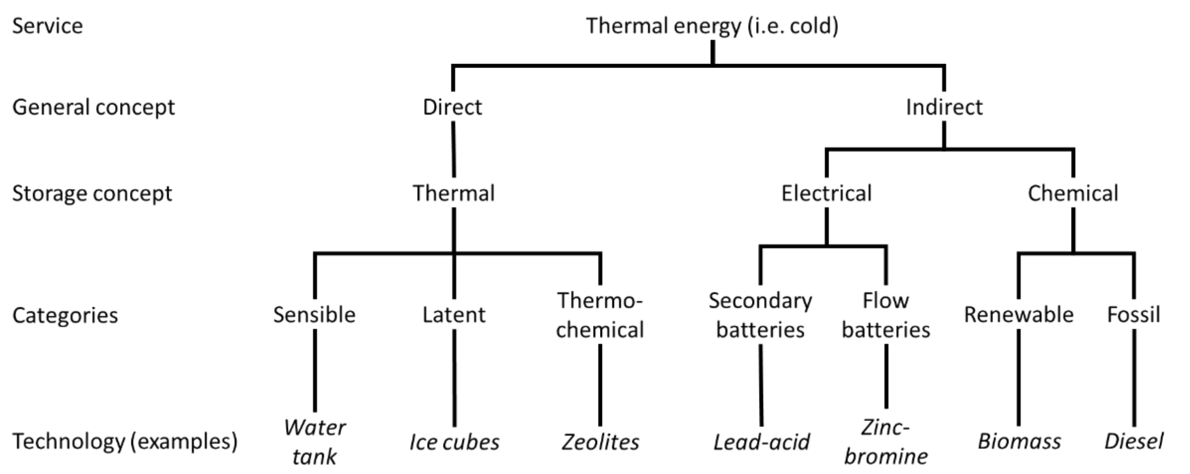


Figure A.5 – Different technology pathways to providing thermal energy.

The three direct cold storage categories are [5]:

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.).

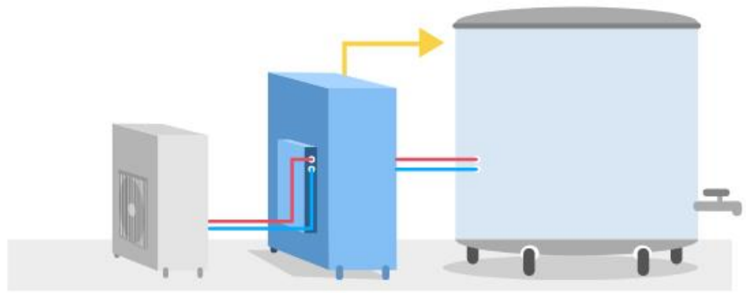


Figure A.6 – Sample cold storage technology, where cold store (middle) was cooled via compressor (left) when electricity was available (in parallel to cooling the tank) and directly cools tank (right) during an outage without requiring electricity.

Appendix: Supporting data – Lithium ion

Table A.1 – Supporting data from interviewed companies on Li-ion battery packs.

Technology	**LFP**	**LFP**	**Li-ion (Not specified)**	**Li-ion (Not specified)**	**LFP**	**LFP**	**Li-ion (Not specified)**
Pack size (kWh)	0.022	0.145	151.8	625	0.5	1	90
Pack cost ($/kWh)	318	379	860	450	240	500	350
Transport							
Installation				50		50	
Comments	Low end of range of $7-10 for 6.6V, 3.3 Ah pack	Median $55 in range $40-68, for 12,4V, 12Ah pack	Includes AC-side coupling. Mean of range $830-890/kWh from two actual quotes (Dec 2015, ex works)	Cost includes inverter. Installation estimated as 10% uplift on pack cost. Cost is for 1MW battery with Tesla powerwall (C1.6) given as the example.	Assumed 500 Wh system based on interview responses	SHS using PbA and Li-ion hybrid with 1 prt Li-ion to 2-3 prts PbA, in an overall size 1-10kWh. Supplier does own installation themselves, at 5-10% of system cost	So far only tested Li ion at nano-grid scales, although their overall product offering is of the order 90 kWh
% cost reduction over previous years	0% over 5 years	21% over 2 years	"Expect Li-ion to converge with PbA in future"	16% per year over last few years		"continue to come down but won't go below $250-300/kWh"	"costs are coming down rapidly, with Li-ion as pacemaker, headed to $250/kWh"

Appendix: Supporting data – Lead Acid

Table A.2 – Supporting data from interviewed companies on PbA batteries.

Technology	**PbA (not specified)**	**PbA (not specified)**	**PbA (Not specified)**	**PbA (sealed)**	**PbA (sealed or flooded)**	**PbA (sealed)**	**PbA (flooded)**
Pack size (kWh)	0.2	365.5	10	0.5	3	90	90
Pack cost ($/kWh)	90	615	125	65	100	230	300
Transport	9				2		
Installation			50		10		
Comments	$18 battery pack cost for PbA, in range 17-21 (fluctuation due to Pb price), for 17 Ah, 12 V battery. Transport (shipping) cost $1-2 per unit, compared to $18 per battery, so interpret as about 10% of battery cost	Includes AC-side coupling. Mean of range $545-685/kWh from two actual quotes (Dec 2015, ex-Works)	Cost excludes inverter, monitoring system	15-20% uplift for charge controller	SHS using PbA and Li-ion hybrid with 1 prt Li-ion to 2-3 prts PbA, in an overall size 1-10kWh. Installation at 5-10% of system cost. PbA cost is average of range $60-80/kWh, with sales cost to customer $80-120/kWh. Pack cost includes BMS but not inverter.		
% cost reduction over previous years	"Fallen, but not as much as LFP. About $1 (5%) cost reduction for higher volumes"			"Prices were significantly higher in the past"	"PbA costs somewhat stable"	Costs actually gone up due to a VAT increase in India	

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