Key Assumptions and Concepts on Potential for Solar Electric Cooking

Batteries capable of operating suitably in ‘harsh’ conditions in the developing world

(Research Question 2)

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Contents

Report Summary

Potential for use of solar-derived electrical power in the developing world is increasingly recognised. This report considers electrical energy storage systems for application when hybridised with solar electricity generation. Potential applications range from the localised low power uses that are already seeing initial introduction, to electrical energy storage to promote stability of electrical supply in neighbourhoods or slum areas, through to substantially higher power localised applications such as solar electric cooking.

Consideration of the state of the art in 2015 for introduction of new battery technologies into such contexts highlights the potential of the lithium iron phosphate (LiFP) battery type for such applications. The lithium titanate (LTO) battery type is already employed in transportation applications but has lower cell voltages and energy density which would necessitate a larger energy storage unit; LTO batteries have some perceived advantages in term of power density and cyclability and should also be considered.

The research question posed is ahead of the capability of current common lithium ion battery types to deliver long term, durable performance at high (tropical) temperatures, but arguably not by much in this rapidly advancing field. There can be optimism that lithium ion battery packs will shortly have evolved to a point where they could realistically be taken forward to possible high power applications in the developing world.

The report makes recommendations for implementation in the context of development of energy storage in higher power solar electricity systems with potential for deployment in the developing world:

> ***Recommendation 1:*** A programme of experimentation which should focus on full characterisation of the behaviour of LiFP battery packs (both current and shortly to be released), and (for meaningful comparisons relative to an existing alternative battery pack approach) of sealed lead acid (VRLA, valve regulated lead acid)) battery packs, both with duty cycles appropriate to higher power delivery at elevated temperature, as in solar electric cooking in the developing world. LTO battery packs should also be considered provided the increased associated cost is not seen as a barrier. Safety testing under conditions of thermal abuse is necessary.
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> ***Recommendation 2****:* A life-cycle-based techno-economic-ecological comparison of different energy storage options is also strongly recommended; specifications for the battery management system for such applications in “hot” countries can be developed from such a study. In addition the potential recycling of modern cell systems has to be investigated.
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> ***Recommendation 3****:* Maintain a watching brief on future battery technology developments,
>
> ***Recommendation 4****:* Develop an interface between a prospective solar electric cooking development programme and battery pack manufacturers.
>
> ***Recommendation 5****:*   Consider the potential for extending cycle life and useable electrical energy storage performance by incorporation of supercapacitor components when seeking persistent high electrical power output capabilities.

Lithium ion battery types, packs and arrays suited to solar electric cooking in the developing world appear technically possible, and the potential of the LiFP type is highlighted. There is, however, a current shortage of key, independent data for this particular type of use and duty cycle.

SECTION 1

The Question

The question is phrased as follows:

"Given the technological development in batteries, and their current stated use, what would be the anticipated lifetime of a lithium iron phosphate battery (suitably sized for research question 1) operating in 'harsh' conditions (excessive heat and dust) and discharging for between 40 mins and three hours a day".

The question itself is "unusual" in that it proposes battery storage of electrical energy in high temperature, tropical environments and subsequent use of that stored energy at high discharge rates in the same environments. The current orthodoxy is that both of these requirements (high ambient temperature and high discharge rate) can lead to substantial deterioration of battery durability and cyclability, and in the case of lithium ion batteries to potential safety problems. Of these two requirements, operation at elevated temperature is considered the more potentially damaging.[1] There is nonetheless, as will be seen later in this report, reason to believe that short-term future developments in lithium ion battery packs may lead to designs suitable for the intended applications, including solar electric cooking.

The research question also indirectly stimulates exploration of the properties of, and potential for spin-off in the following areas:

- electro-chemical energy storage systems for application when hybridised with solar electricity generation in developing countries
- subsequent use of that stored solar electrical energy in a range of contexts in the developing world (in residential cities and towns, in slums and in the rural bush), potentially including solar electric cooking.

The "modern" field of lithium ion batteries remains developmental, with continuing changes in battery chemistry (the actual energy materials in individual cells) and in the design of battery packs (groups of cells assembled and engineered with a view to particular applications). It is therefore important, at the outset, to distinguish clearly between individual cells (such as the well-known AA "battery" type) and engineered battery packs (of which the lead-acid batteries used in transportation are examples).

The research question is not yet answerable without a programme of work to study lithium ion battery packs (those currently available and those shortly to be launched) at elevated temperatures and under high power discharge, and it will be correct to evaluate the performances obtained relative to the well-established lead acid batteries already adopted for low power applications in the developing world. Further, it will become evident that a single, car-battery-type battery pack will not be sufficient to achieve the goal of implementable solar electric cooking – an array of such packs (or a higher voltage, larger electrical energy storage capacity pack) would be needed.

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[1] Johnson Matthey Battery Systems, personal communication. (December, 2015)

Potential applications range from the localised low power uses that are already seeing initial introduction, to electrical energy storage to promote stability of electrical supply in neighbourhoods or slum areas, through to substantially higher power applications such as solar electric cooking. Much of the discussion below relates to contexts in sub-Saharan Africa but there is potential for application throughout the developing world, thereby “greening” energy usage and reducing greenhouse gas and particle emissions (for instance, by significant reduction in the perceived need for kerosene and charcoal as fuels).

1.1 The Context

The potential for use of solar-derived electrical power in the developing world is increasingly recognised,[2] as is its potential for electrification in rural bush areas.[3] In Kenya there is already implementation in small scale solar farms [4] and application of much lower power devices is being promoted by NGO’s and via a hire-and-pay-back funding mechanism, for instance in slums in Nairobi.[5]

There is currently only low usage of electrical energy for cooking in the developing world, particularly when away from urban locations. It is important to distinguish between solar cooking (using direct heating by the sun’s rays alone), electrically assisted solar cooking (in which there is an additional low power electrical heating) and solar electric cooking (in which only electrical power heats the food). The potential for the last of these (which requires the highest electrical power) is the primary context of this report and has been little explored, though reported in a brief, mistaken programme title for an Indian government funded small project which actually concerned a solar electric cooler (a chiller as opposed to a cooker).[6]

There are several areas in addition to cooking where stored solar electrical energy could play a significant role in developing countries. The existing electrical grids in the developing world are of low stability, with “brown outs” (intermittent losses of voltage and power from the grid) being commonplace;[7] this can be seen as an opportunity for localised electrical energy generation and storage for applications such as backup power, load levelling (reducing power fluctuations for the user) and even for use in stabilising telecommunication systems such as cell phone networks (where transmitter masts need to be reliably powered, currently with back up diesel {fossil fuel} generators of electricity).

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[2] Powering the developing world with solar? https://crowd.sunfunder.com/projects/view/31 (accessed 14 October 2015)

[3] Could renewable energy make rural electrification a reality? http://www.theguardian.com/global-development-professionals-network/2014/aug/06/rural-electrification-renewables-solar-energy (accessed 14 October 2015)

[4] Go-Solar Systems Ltd, http://www.gosolarltd.com/ (accessed 14 October 2015)
Powergen Renewable Energy (Nairobi), http://powergen-renewable-energy.com/about-pre/ (accessed 14 October 2015)

[5] PAYGO Solar for Nairobi Slums, https://crowd.sunfunder.com/projects/view/31 (accessed 14 October 2015)

[6] Project profile on electric/solar cooker (2010-12), www.dcmsme.gov.in/reports/electronic/electricsolarcooker.pdf (accessed 14 October 2015)

[7] Southern Africa: brownouts inevitable, http://allafrica.com/stories/200801230370.html (accessed 4 November 2015)

The purpose of this report considering Research Question 2 is to examine the current state-of-the-art in available battery technologies for storage of electrical energy, with particular emphasis on suitability for developing world contexts. The discussion will consider the level of development and availability of applicable batteries, and discussion will necessarily consider the characteristics and use of batteries at a range of power levels and with widely differing electrical charge storage capacities (in units of ampere hours, A.h). Solar electric cooking, for instance, requires a much higher power level, and much more stored energy, than is necessary for night time lighting, but both applications constitute use of stored solar electricity.

SECTION 2

Battery technology – the current relevant state-of-the-art

2.1 Terminology

A *battery* is an assembly of a number of individual electrochemical cells designed and configured to store electrical energy. Most commonly this assembly is within a package, constituting a *battery pack* such as the familiar lead-acid battery used in vehicles. *Primary batteries* can be used/discharged only once, but rechargeable (*secondary*) batteries can be charged and discharged many times, the number of times this can be done satisfactorily defining the *cycle life.* Within the cells, matter (as ions) is transferred between electrodes during charge and discharge, this process constituting the *battery chemistry.* For cyclic usage, as in vehicles and in temporary storage of renewable electricity, rechargeable batteries with long cycle lives and low costs are required.

Many battery chemistries and technologies have been developed historically. The most familiar rechargeable battery packs are of the lead-acid type, in which water is the solvent. Modern types have evolved into systems which can operate at reasonably high stored energy densities and can support high depth of discharge (DoD), which is the amount of stored electrical charge that can be accessed in usable charge-discharge cycles; a 25% DoD, for example, means that 75% of the capacity for stored charge (in A.h) in the battery is not available during cycling. Individual lead-acid cells can be large and connected in series. Modern high capacity and high DoD lead-acid battery packs are “sealed” and connected in series, with various configurations possible and the most commonly employed in energy storage being of the valve regulated lead-acid type (VRLAs). Consumer electronics can be powered by other aqueous rechargeable battery types such as Ni-Cd (NiCad) and nickel metal hydride (NiMH) types; such batteries substitute for primary batteries (e.g. AA battery geometry) but do not have high charge storage densities or stored energy densities (the former measured in ampere hours per gram, $A.h.g^{-1}$), ruling out their use in larger scale applications. Furthermore, cadmium (Cd) is highly toxic (Cd use in Europe is severely limited) and NiMH battery types use metals some of which are expensive and seen as critical resources.

“C rate” is a measure of how fast a battery is charged and discharged. The electrical energy potentially available from a battery is linked to the current(s) at which the battery is discharged (the relevant equations are *charge stored = current x time* and *power = current x voltage*). A battery that would be fully discharged in 1 hour has been discharged at 1C, while one that would be discharged in 2 hours is discharged at C/2 (0.5 C); some show the latter as C_2. The charge storage capacity (in units of ampere hours, A.h) of a battery depends on the C rate,[8] with capacity decreasing as C rate increases. Manufacturers of rechargeable batteries typically quote capacities at C/20 (0.05C, discharge over 20 hours), to provide a “good” capacity value. In this study, however, significantly higher C rates will be involved, for example total discharge over 4 hours (C/4), with consequent substantially reduced capacity.

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[8] What is the C-rate? http://batteryuniversity.com/learn/article/what_is_the_c_rate (accessed 30 October 2015)

2.2 Modern battery chemistries

Battery types that have been under development since the 1960s for large scale energy storage include the sodium-sulfur (Na/S) battery, redox flow batteries, and *lithium batteries* (of which there are many types). The sodium–sulfur battery operates at temperatures above 300^{o}C, ruling out use in the home or small scale, and in demonstration plants for larger, grid-scale application safety concerns have re-emerged.[9] An alternative, NaNiCl (NaCl/Ni chemistry), battery type has been developed for high temperature use in stationary storage and is claimed to be better performing and safer than Na/S.[10]

Redox flow batteries (RFBs) store electricity in 2 flowing, usually corrosive, aqueous liquids and are envisaged as for approaching-grid-scale application (there are already demonstrator projects mounted on a number of grids). The most common RFB type is the all-vanadium redox flow battery (VRFB), which has been studied at temperatures of up to 55^{o}C;[11] the batteries continue to operate, but with increasing capacity degradation at increasing temperatures. An alternative approach using non-corrosive chemistry has been reported very recently,[12] and a German project is focused on large scale wind power + RFB application, the "Redoxwind" project.[13] VRFBs are beginning to be marketed for domestic/home application [14] and there is increasing application experience evident from a number of manufacturers e.g. [15]. A persistent issue with current RFB technology is the low associated energy density (solutions cannot be concentrated); RFBs are therefore bulky units containing large volumes of reactive liquids and there are inherent complexities of electrical and pumping control. RFBs can have durable cycling, but cyclability degrades at elevated temperatures. On balance, RFBs seem unlikely to be technologically suited to implementation at small scale in the developing world other than in major population centres. There could, however, be scope for their implementation in grid stabilization.

Lithium batteries, on the other hand, have become increasingly familiar. The use of this alkali metal leads to higher cell voltages (and energy densities *etc.*) being accessible but requires a non-aqueous (water-free) electrolyte in the cells; lithium metal itself reacts with water, and the high cell voltages would lead to electrolysis of water ("gassing"). A possible issue into the future for all lithium-based batteries is that lithium is not an abundant element, and so sustainability could become an issue in the event of steeply increasing usage.[16]

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[9] Exploding sodium sulfur batteries from NGK energy storage, https://www.google.co.uk/webhp?sourceid=chrome-instant&ion=1&espv=2&ie=UTF-8#q=Exploding-Sodium-Sulfur-Batteries- (accessed 14 October 2015)
Cause of NAS Battery Fire Incident, Safety Enhancement Measures and Resumption of Operations, http://www.ngk.co.jp/english/news/2012/0607.html (accessed 14 October 2015)

[10] Sodium Nickel Batteries, http://www.fiammsonick.com/ (accessed 5 November 2015)

[11] Effects of operating temperature on the performance of vanadium redox flow batteries, C.Zhang, T Zhao, Q Xu, L An, G Zhao, Applied Energy, 2015, 155, 349-353

[12] An aqueous, polymer-based redox-flow battery using non-corrosive, safe, and low-cost materials, N Martin, U Martin, C Friebe, S Morgenstern, H Hiller, M Hager, U Schubert, Nature, 2015, 527, 72-81 (accessed 11 November 2015)

[13] Large scale project „Redoxwind", http://www.ict.fraunhofer.de/en/comp/ae/rfb/redoxwind.html#tabpanel-1 (accessed November 11th 2015)

[14] Everflow Compact Storage: Energy Anytime, Anywhere; http://schmid-energy-systems.com/en/schmid-energy-systems.html (accessed November 5th 2015)

[15] http://energy.gildemeister.com/en/; http://redflow.com/products/; http://www.vanadiumbattery.com/; http://www.vanadiumredoxflow.com/; http://www.vanadispower.com/; http://www.redtenergy.com/ (UK) (accessed November 11th 2015)

[16] S **Ziemann, A Grunwald, L Schebek, D Müller, M Weil,** The future of mobility and its critical raw materials. Revue de Métallurgie, 2013, 110, S. 47-54

Recycling of lithium use in transportation battery packs poses a challenge into the future.[17] Lithium batteries continue to evolve, particularly with new battery chemistries being developed to overcome the shortcomings of existing designs (enabling higher discharge rates and seeking durability and cyclability that persist to higher temperatures).

The highest energy density batteries available contain an inorganic lithium salt (such as $LiPF_6$, lithium hexafluorophosphate) as electrolyte dissolved in an organic solvent such as a mixture of organic carbonates (the solvent is flammable in lithium batteries); the electrolyte solution impregnates a separator between two electrodes, an anode (carbon {C}, or a lithium alloy or electrochemically similar compound) and a cathode (a compound in which Li is stored on charging the battery). The first generation of these *lithium ion batteries* was developed in Europe by Goodenough (then at Oxford) and others, leading to the $C/LiCoO_2$ (lithium cobalt oxide battery, “Sony battery”) type; subsequent work led first to systems containing anodes such as $LiMn_2O_4$, which has a lower cyclability.[18] Cathodes of the type $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA) are used in cells in the Tesla all-electric sports car, in light of its perceived very high power output;[19] that chemistry, nonetheless, also has a lower cyclability relative to $C/LiCoO_2$. The $C/LiCoO_2$ and C/NCA battery types have a number of issues: battery control electronics are needed to prevent thermal runaway (a potential fire hazard); the batteries do not support a high DoD, limiting available energy; cobalt itself (Co) is highly toxic, which is a further incentive to a rigorous recycling approach (additional to concern to conserve Li sustainability).

A high charge rate lithium ion battery, the lithium titanate (LTO) battery, results from replacing the carbon anode with $Li_4Ti_5O_{12}$ that has particles at the nanometre scale; the replacement results in higher current densities (and high C rates, see later) being achievable, but at the cost of a lower battery voltage overall (and hence reduced energy storage density and a requirement for larger units). This approach contrasts with what had otherwise become the orthodoxy, that future batteries should have higher voltage outputs. Further, high C rate usage results in reduced cyclability and the LTO type is more expensive than other lithium ion types. The cathode is, however, $LiCoO_2$ which has inherent drawbacks (toxicity of Co, decomposition at moderate temperatures). Nonetheless, battery packs of this type are being employed in transportation in light of the perceived advantages of high cycle stability, a broad operating temperature range, and availability of high C rates;[20] these batteries are produced by Toshiba, Altairnano and Leclanché e.g. [21].

More recently, Goodenough and others have developed the lithium iron phosphate battery type (LiFP battery, $LiFePO_4$ cathode). This type has significant advantages relative to earlier lithium ion batteries: increased available DoD (higher energy storage capacity); increased safety (e.g. to higher temperature).[22] The power density is, however, slightly lower (relative to the lithium cobalt oxide type) due to the inherently low electronic conductivity of the cathode material. This cell type has been taken to market by A123 (USA) and other companies, and is also being taken forward as a potential basis for grid-scale energy

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[17] M. **Weil, S Ziemann,** Recycling of traction batteries as a challenge and chance for future lithium availability. In: G Pistoia: Lithium-Ion Batteries: Advances and applications. S. 509-528 (Amsterdam, Elsevier 2014)

[18] The Li-Ion rechargeable battery: A perspective, JB Goodenough and K Park, Journal of the American Chemical Society, 2013, 135, 1167-1176

[19] Types of lithium ion batteries, http://batteryuniversity.com/learn/article/types_of_lithium_ion (accessed 5th November 2015)

[20] Lithium Titanate (LTO) Cells - Technical Advantages, http://www.ev-power.eu/LTO-Tech/ (accessed 11 November 2015)

[21] Characterization of NCA/Li-Titanate Cells, http://www.leclanche.eu/img/pdf/Test%20Reports/Test%20Report%20Hochschule%20Landshut%202014-01-30.pdf (accessed 11 November 2015)

[22] A comparative study of lithium-ion batteries, M.Oswal, J Paul, R Zhao, University of Southern California (2010), http://www-scf.usc.edu/~rzhao/LFP_study.pdf (accessed 14 October 2015)

storage (again by A123). Battery packs outwardly similar to VRLA packs (outside appearance as for a car battery) are now commercially available. An ongoing concern on loss of safety on scale up of small lithium batteries does, however, necessitate a substantially more complex arrangement of individual *small* cells in the LiFP case (and all Li ion types), along with some battery management electronics and an intelligent passive cooling system.

Other battery types still exciting developmental interest include the lithium sulfur (Li/S) battery, the "lithium-air" battery (actually Li/O_2) and, most recently, sodium ion batteries. The lithium sulfur battery is portrayed as being more robust than lithium ion batteries, and suited to harsher conditions (e.g. for military applications).[23] The effort is led in Europe by Oxis Energy (Oxfordshire),[24] with North American interest also persisting.[25] The principal issue in the further development of that chemistry is loss of sulfur from the cathode in operation, which limits cyclability and progressively lowers charge storage in use.[26] The attraction of the lithium-air battery is the, in principle, very high voltage accessible but, as with other metal-air battery types, there are considerable problems with cyclability (and also with moisture and CO_2 in air itself); further, electrode oxidative destruction and solvent polymerisation have also been issues. Research into that system has been largely discontinued by industry.[27] An attraction of the sodium ion approach is the sustainability of sodium (in contrast to the resource criticality of lithium). Advance in sodium ion batteries has been rapid and led in Europe by Faradion (a SME company based in Sheffield); research has already progressed to initial battery packs.[28] There is, however, as yet little public domain data comparing the safety of Na ion and Li ion batteries (sodium metal itself is more reactive than is lithium). High voltage, non-aqueous (water-free) sodium ion cells should not be confused with the lower voltage saltwater cells (water as solvent, aqueous hybrid ion batteries) developed and being marketed by Aquion Energy in the USA [29]; the energy density for non-aqueous (higher voltage) sodium ion batteries will be likely to be much higher than any aqueous system.

2.3 Battery types relevant to the research question

On the basis of the above discussion, and at the time of writing of this report, the clear leaders in terms of robustness, cost and ability to deploy are the VRLA (sealed lead acid) and LiFP (lithium iron phosphate) battery pack types. If cost is not a major issue, the LTO battery type can be added to this list and is already commercially available. The older, flooded lead acid battery types have been superseded and the first generation lithium ion

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[23] Lithium-sulfur rechargeable battery safety, Sion Power www.sionpower.com/pdf/articles/PowerSources2004.pdf (accessed 15th October 2015)

[24] Oxis Energy: Lithium Sulfur Battery Technology, www.oxisenergy.com (accessed 14 October 2015)

[25] Polyplus Battery Company, http://www.polyplus.com/lisulfur.html (accessed 15th October 2015)
Sion Power – the Rechargeable Battery Company (accessed 15th October 2015)

[26] Lithium–sulfur batteries: electrochemistry, materials and prospects Y Yin, S Xin, Y Guo, L Wan, Angewandte Chemie 2013, 52, 13186 – 13200
Liquid electrolyte lithium/sulfur battery: fundamental chemistry, problems, and solutions, S Zhang, Journal of Power Sources 231 (2013) 153-162
2014 http://sciencewatch.com/articles/lithium-air-batteries-are-great-so-are-their-problems (accessed 4 November 2015)
The rechargeable revolution: a better battery, R van Noorden, Nature, 2014, 507-508
Lithium-air : two big labs step back from the most promising next generation battery, http://qz.com/214969/two-big-labs-most-promising-next-generation-battery-electric-car/ (accessed 14 October 2015)

[28] Faradion – sodium ion technology, http://www.faradion.co.uk/technology/sodium-ion-technology/ (accessed 14 October 2015)
Sodium-ion batteries 'set to challenge' dominant lithium-ion technology, The Engineer, 15 May 2015 http://www.theengineer.co.uk/energy/news/sodium-ion-batteries-set-to-challenge-dominant-lithium-ion-technology/1020369.article (accessed 15 October 2015)

[29] Aquion Energy, http://www.aquionenergy.com/ (accessed 5 November 2015)

battery types have been problematic in some regards and may well be superseded by the LTO or LiFP types, or types still under development. Sodium-sulfur batteries and redox flow batteries are not envisaged as being widely applicable in the developing world, and major industrial and government laboratories have withdrawn from pursuing the problematic lithium-air battery.

The lithium-sulfur and sodium ion battery types are both the subject of considerable ongoing investment. Developments in these areas need to be monitored. The lithium-sulfur option becomes attractive if low cyclability can be overcome, and the sodium ion option may rapidly become competitive with lithium ion near equivalents.

The issue of competing claims by the manufacturers of differing battery technologies needs to be taken seriously. There is a case for detailed evaluation and metrology; this could involve studies at, and with institutions such as the National Physical Laboratory or the HVM Battery Catapult at Warwick.[30]

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[30] WMG centre HVM Catapult, Energy Innovation Centre https://www2.warwick.ac.uk/fac/sci/wmg/research/hvmcatapult/research/energyinnovationcentre/ (accessed 5 November 2015)

SECTION 3

Current and potential future uses of batteries in static solar electrical power in developing countries

Uses highlighted above such as lighting, backup, load levelling and solar electric cooking constitute applications suited to static, as opposed to in-vehicle electrical power. In the case of a static power system, the mass of the storage device is not a major issue, nor are those of the individual cells and battery packs.

Hybrid solar electricity systems, such as those utilising generation of solar photovoltaic electricity + electricity storage for later use, can range from small systems (for lighting), through to a small array of battery packs (solar electric cooking) and up to a large plant for backup of an unreliable grid or micro-grid (e.g. a small town or rural settlement). The applications could therefore be as standalone hybrid systems or as part of a wider network or grid. Related battery storage of electrical energy could also be used at a large scale without solar electricity input, for example in stabilising a grid or in providing a locally uninterruptable power supply (UPS) for continuity of cell phone networks.

In an African context, domestic solar electricity is already being introduced, charging batteries and also feeding in to a local micro grid or a wider grid.[31] Electric cooking might be one possible use of that electricity, so long as the capacity of the energy storage system is adjusted. Solar power at a smaller scale (e.g. night time lighting and other low power applications) is being introduced e.g. [32].

The battery of choice in solar electricity installation has largely been the lead-acid type, based on its widespread use in many contexts and on its perceived robustness. VRLAs are a proven type with deep depth of discharge and historically extended experience of its use; an example of such a battery type is the Sonnenschein "gel" battery range,[33] which has been employed in a range of challenging applications. An example where this battery class was chosen on the basis of perceived durability and low purchase price (in light of a limited budget) is the installation of small scale solar power by an NGO that twins villages in Anglesey and the Gambia; the Amlwch–Sankwia project,[34] a recipient of a United Nations Gold Star Communities Award, has provided solar electricity to power lighting and a water pump in Sankwia, with electrical energy stored in VRLA battery packs as power for a small hospital.

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[31] Go-Solar Systems Ltd, http://www.gosolarltd.com/ (accessed 14 October 2015)
Powergen Renewable Energy (Nairobi), http://powergen-renewable-energy.com/about-pre/ (accessed 14 October 2015)

[32] PAYGO Solar for Nairobi Slums, https://crowd.sunfunder.com/projects/view/31 (accessed 14 October 2015)

[33] Sonnenschein *dryfit Gel* Batteries. http://www.sonnenschein.org/ (accessed 5 November 2015)

[34] Cefyllion Sankwia Friends, http://www.sankwia.org.uk/ (accessed 15 October 2015)

A number of nationalities take developmental and commercial interest in solar power in Africa. Thus developmental projects involve, for instance, Norway[35] and Germany[36], and the Amlwch–Sankwia project (above) is an example of small scale British NGO involvement. A China-Kenya Solid State Lighting Project has been established near Nairobi,[37] building on the availability of low cost Chinese solar PV panels. Battery suppliers in East Africa are, nonetheless, lobbying for protection from an “onslaught” of imported, low cost, Chinese battery technology (VRLA type).[38] A high electrical power spin-out from the vehicle industry has been proposed by the Tesla company (USA), with plans announced for moving into commercial and residential storage.[39] The proposed Tesla Powerwall is an array of lithium ion batteries, an approach also suggested below, and the in-principle potential for this in providing medium scale (e.g. domestic) electricity storage in Africa has already been recognised.[40]

The high power battery packs considered below are sealed units in configurations that are related to low power installations already being implemented in Africa. Maintenance of such battery arrays is seen as a minor issue compared to the wider issues associated with service and maintenance of a small scale, hybrid, solar electricity generation and storage resource/system, whatever the location of that system might be (urban, slum, rural bush).

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[35] Solar energy provides electricity in remote areas, http://sciencenordic.com/solar-energy-provides-electricity-remote-areas (accessed 15 October 2015)

[36] Powering the developing world with solar, http://www.dw.com/en/powering-the-developing-world-with-solar/a-18540494 (accessed 15 October 2015)

[37] Solar power: China-Kenya training centre launches in Nairobi, April 2015 http://www.esi-africa.com/solar-power-technology-training-centre-launches-in-nairobi/ (accessed 15 October 2015)

[38] The market for batteries in East Africa, http://www.africa-business.com/features/battery-africa-market.html (accessed 15 October 2015)

[39] Tesla's new batteries may be harder on the environment than you think, The Guardian, 10 June 2015 http://www.theguardian.com/vital-signs/2015/jun/10/tesla-batteries-environment-lithium-elon-musk-powerwall (accessed 15 October 2015)

[40] Africa's next 'leap frog': Five big impacts the Tesla battery could have on the continent in future, Mail Guardian, Mail & Guardian (South Africa) 7 May 2015 http://mgafrica.com/article/2015-05-07-a-battery-with-a-big-impact-tesla (accessed 15 October 2015)

SECTION 4

Robustness, tolerance of dust and heat, and safety

4.1 Robustness

The robustness (in terms of performance and durability) of a battery in its local conditions is not a feature of the battery chemistry alone. Other factors include:

- The packaging and protection of the pack from dust. The engineering of a "clean" environment for the battery (inside an exterior packaging) is straightforward provided the operating environment is adequately ventilated. The pack is typically sealed and so dust is not a major operational issue.
- Its location and ventilation (the ambient temperature of the battery environment should not be allowed to become too high). In sub-Saharan Africa this means avoidance of placing in direct sunlight and of both storage and operation in a construction within which the temperature could rise very substantially either due to battery use or external solar heating; a construction of that type could otherwise be hazardous for storage and use of a lithium ion battery the electrolyte in which is typically an inorganic salt dissolved in a flammable, volatile organic compound. High temperature is also deleterious to lead acid battery types.
- Its duty cycle. As first introduced in 2.1 above, the usable capacity of a battery depends on the accessible depth of discharge (DoD), which is a measure of the charge actually available to power the load; a battery which can only support a DoD of 50% can supply only 50% of the stored charge to the load. Usable DoD depends on the detailed battery chemistry. The applied DoD has a strong influence on cycle life and should represent a balance between minimum state of charge versus lifetime and economics (the lower the DoD the higher the amount of not useable capacity and not useable stored energy). Studies of the effect on cycling on battery life have been reported recently,[41] but there does not seem to be any public domain data concerning the drop in capacity for LiFP batteries at very high C rates and elevated temperature; a drop of 50% or more could, however, be possible, particularly after extended cycling at high temperature.

An elevated temperature for a battery is said to increase its capacity but high temperatures are known to lead often to reduced battery lifetime (in storage and in operation),[42,43,44] as discussed below. In the case of lithium ion batteries, there is the additional complication that the batteries can potentially catch fire at considerably elevated temperatures (flammable organic solvents are necessarily employed); this is discussed further in the next sub-section. There have been a number of publications studying the detail of degradation within lithium

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[41] Cycle ageing analysis of a $LiFePO_4$ /graphite cell with dynamic model validations: Towards realistic lifetime predictions, E Sarasketa-Zabala, I Gandiaga, E Martinez-Laserna, LM Rodriguez-Martinez, I. Villarreal, Journal of Power Sources, 2015, 275, 573–587

[42] http://pvcdrom.pveducation.org/BATTERY/capacity.htm (accessed on 30 October 2015)

[43] Extreme summer heat can burn up car batteries, http://www.carcare.org/2012/07/extreme-summer-heatcan-burn-up-car-batteries-2/ (accessed 15 October 2015)

[44] Heat tolerance of automotive lead-acid batteries, J Albers, Journal of Power Sources 2009, 190, 162–172

ion cells at elevated temperatures (e.g. at up to 55ºC [45,46]); changes in the electrodes are responsible for the increasing degradation rate of the charge storage capacity at elevated temperature. Saft (France) has nonetheless developed Li ion batteries that can be used at up to 125ºC and that are capable of 300 cycles at 80ºC,[47] encouraging optimism for durability in elevated temperature operation in the developing world; those batteries are currently considerably more expensive than less specialised Li ion batteries. The company Tadiran (a wholly-owned subsidiary of the Saft Group) offers a commercially available Li (hybrid?) battery for elevated temperature and harsh environments.[48] At high temperature currently available cells have to be protected against high charge and discharge currents, which makes necessary a smart working battery management system [49] and implies a restricted energy and power availability during high temperature operation.

The power delivery is given simply by *power = current x cell voltage* (the latter varies during cell discharge). A naïve calculation based on a current demand of 3 A by a load for 3 hours results in a total of 9 A.h of electrical charge being required. A "12A.h" battery pack might then seem adequate, but at a low voltage, say 12 V, the consequently high C rate (C/1 in this case) could dramatically reduce the capacity, and the usable DoD would also be less than 100%. The naïve conclusion would then be that a "24 A.h" battery pack (or one with an even higher "capacity") could be necessary. Alternatively, use of a higher cell voltage (for instance a nominally 48 V battery pack) would lower the required current power output. Further, an increase in capacity would also enable a decreased C rate and a decreased DoD per cell, leading to an increased cycle life for the battery pack. In the case of LiFP battery packs, commercial single packs at 100 A.h are becoming available (e.g. as listed by Battery Masters [50]).

A discussion of the effects of a high charge rate on the battery pack itself, and hence of high currents, is given in, for instance, "Characteristics of Rechargeable Batteries" (from Texas Instruments).[51] High discharge currents (and high applied voltages during charging) can cause significant damage to battery performance, and are characteristic of transients occurring on "switch on"; this is potentially directly relevant to this solar electric cooking project, where average currents in use could correspond to C/4 discharge, or even greater C rates, and initial currents drawn are potentially much higher (the initial electrical resistance of heating elements is low).

A modern approach (e.g. highlighted in an on-line forum hosted by Tesla Motors [52]) could be to hybridise the battery pack to include a supercapacitive circuit element, thereby smoothing the power demand and increasing the lifetime of the battery and with the side benefit that available energy would also be slightly increased (the highest C rates are then not accessed). Supercapacitors (SCs) are not necessarily expensive, though the opposite is a commonly held view representing the current market price. Capacitors such as Maxwell's

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[45] Effect of temperature on the ageing rate of Li ion battery operating above room temperature, F Leng, C Tan, M Pecht, Scientific Reports, 2015, 5, article number 12967

[46] Capacity fade of Sony 18650 cells cycled at elevated temperatures: Part 1, Cycling Performance, P.Ramadass, B. Haran, R White, B Popov, Journal of Power Sources, 2001, 112, 606-613

[47] Rechargeable high temperature lithium-ion battery VL 25500-125, Saft Doc. No 54060-2-0309 www.saftbatteries.com/force_download/VL25500_125.pdf (accessed 9th December 2015)

[48] TLI Series Long-Life Rechargeable Lithium-ion Batteries, http://www.tadiran.com/index.php/tli-series-rechargeable (accessed 21 December 2015)

[49] Tadiran Batteries, Technical Notice LTN-065-46-a, Guidelines for the usage of TLI cells, http://www.tadiranbatteries.de/pdf/TLI-guidelines.pdf (accessed 21 December 2015)

[50] LiFePO$_4$ batteries https://www.batterymasters.co.uk/Catalog-LiFePO4-Batteries_299.aspx (accessed 5 November 2015)

[51] Characteristics of rechargeable batteries, Texas Instruments literature SNVA533 (2011). Available at http://www.ti.com/lit/an/snva533/snva533.pdf (accessed 30 October 2015)

[52] http://my.teslamotors.com/forum/forums/will-tesla-hybridise-its-batteries-supercapacitors-already (accessed 30 October 2015)

Boostcap range employ volatile organic solvents (acetonitrile) and are indeed expensive to manufacture (requiring dry room assembly plants and thermal drying of electrode films) but development of water-based supercapacitors to compete with these and which could be very much cheaper to manufacture is currently a highly topical research theme.[53,54] Current research on aqueous supercapacitors is leading to considerably extended cycle lives, an area which had previously been a concern; low cost, high capacitance, aqueous supercapacitors are nonetheless a RD&D targeted deliverable and therefore unlikely to be implemented in the short term.

4.2 Safety at elevated temperature

There is a comparatively mature understanding of the behaviour of lead-acid batteries at up to 60^{o}C,[55] including corrosion leading to capacity loss. Electrode corrosion is the dominant factor for classical, flooded lead-acid batteries and water loss is an additional factor for valve-regulated systems (VRLAs). VRLA types are found to be highly durable and superior in their behaviour in this respect, relative to flooded types.

There are issues with lithium ion batteries at elevated temperature that are not characteristic of lead-acid battery types and the possibility of fire is one feature that has received widespread publicity.[56] As discussed above, more sophisticated battery management is needed for the prevention of thermal runaway and for other features of pack management; there are also further issues to address that result from the battery chemistry itself. Thus there are historical, very occasional instances of laptop computer batteries igniting in use, with those occurrences having been assigned to problems in the manufacture of the batteries which led to internal short circuiting.[57] The Li ion battery pack deployment in the Boeing Dreamliner was also problematic, including a fire in a Dreamliner at London's Heathrow Airport.[58] Both of these relate to an "old" battery technology ($C/LiCoO_2$) which is not seen as suited to solar electric cooking; LiFP is, as stated above, considered a safer battery chemistry, with an enhanced cyclability of energy and power densities, relative to the older technology.

Battery packs envisaged as deployable under this solar electric cooking project would be much less complex than those deployed for aerospace applications. Fundamental aspects of the chemistry within individual cells can limit the maximum operating temperature for a Li-ion battery.[59] For single cells, a detailed study of lithium ion battery types under thermal runaway conditions relates their safety to composition, size, energy content, design and quality;[60] the LiFP cell showed the best safety characteristics of the cells tested, and safe

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[53] A review for aqueous electrochemical supercapacitors, C Zhao and W Zheng, Frontiers in Energy Research, 2015, vol 3, article 23

[54] Electrochemical energy storage to power the 21st century: Asymmetric electrochemical capacitors – stretching the limits of aqueous electrolytes. JW Long, D Belanger, T Brousse, W Sugimoto, MB Sassin, O Crosnier, MS Bulletin, 2011, 36, 513-522

[55] Heat tolerance of automotive lead-acid batteries, J Albers, Journal of Power Sources, 2009, 190, 162–172

[56] Why lithium batteries keep catching fire, http://www.economist.com/blogs/economist-explains/2014/01/economist-explains-19 (accessed 15 October 2015)

[57] ComputerWeekly.com, May 2007. http://www.computerweekly.com/feature/Dell-Laptop-Battery-Recall-The-Expert-View (last accessed 30 October 2105)

[58] http://www.theguardian.com/business/2015/aug/19/lithiumbatteryreviewboeingdreamlinerfireheathrow (last accessed 15 October 2015)

[59] A review on the key issues for lithium-ion battery management in electric vehicles, L Lu, X Han, J Li, J Hua, M Ouyang a, Journal of Power Sources 2013, 226, 272-288

[60] Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivine-type cathodes. A Golubkov, D Fuchs, J Wagner, H Wiltsche, C Stangl, G Fauler, G Voitic, A Thaler, V Hacker, RSC Advances, 2014, 4, 3633–3642

performance has been reported in the range 65-90^{o}C. [61] Some electrolyte solutions are reported to decompose at as low as 69^{o}C; an internal solid electrolyte layer is reported to decompose at 90-120^{O}C; cathode materials can decompose on reaching elevated temperature (e.g. $LiCoO_2$ at 150^{o}C, but $LiFePO_4$ at the much higher 310^{o}C). The high onset temperatures for decomposition for $LiMn_2O_4$ and $LiFePO_4$ suggest that cells with those cathodes could be more resistant to thermal abuse, and the reduced peak self-heating rate for LiFP batteries is claimed to make them the safest lithium ion batteries currently marketed.[62] Choice of battery chemistry is thus important in fire prevention and considerable effort is therefore being expended on refinement of that chemistry to increase safety margins [63]. To that end, ionic liquid compounds in combination with a majority alkyl carbonate solvent in a mixed solvent system (reducing flammability) are currently topical.[64] Purely ionic liquid solvents have also been explored;[65] very low volatility of the solvent is advantageous but high electrolyte resistances limit power. A recent report concerns a quasi-solid, ionic-liquid-plus-clay, composite electrolyte, [66] but still with high electrolyte resistance. Truly solid electrolytes (ceramic materials) continue to be topical,[67] but their applicability is likely to be at substantially higher temperatures than are relevant to this report. The area of alternative, inherently safe, high conductivity electrolytes therefore remains developmental.

4.3 Characteristics of commercial VRLA and LiFP battery pack types

The 12 V *Powersonic ps12120* lead acid battery pack is listed as having a 12 A.h capacity and a current price of ca. £23 (prices exclude VAT).[68] It is stated as having an operational temperature range with an upper limit of 60^{o}C; the associated data sheet lists only normal fire hazards resulting from combustion; sulfurous gases and carbon monoxide (the battery chemistry itself does not pose a fire hazard). The *Tracer* 12 V 24 A.h pack is a C/$LiFePO_4$ (LiFP) battery pack with a current price of £249 and also has a stated operational temperature range also with an upper limit of 60^{o}C;[69] related packs are available at down to 4 A.h capacity (on a C/20 basis) and at reducing costs (8 A.h at £199). For both battery pack types, the stated maximum operational temperature is therefore similar. For these commercially available battery packs the stated maximum current outputs (36 A for the lead acid pack and 30 A for the LiFP pack) are also similar. The *current* selling price for delivery of similar currents of around 30 A (by the *Powersonic* 12 A.h VRLA and the *Tracer* 24 A.h devices) is, however, considerably lower for the lead acid type than for the LiFP type, and it is evident that a higher capacity unit (in A.h) is needed for an LiFP unit to deliver the same current as a VRLA.

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[61] A comparative study of lithium-ion batteries, M.Oswal, J Paul, R Zhao, University of Southern California (2010), http://www-scf.usc.edu/~rzhao/LFP_study.pdf (accessed 14 October 2015)

[62] A general discussion of Li ion battery safety, D Doughty, E Roth, The Electrochemical Society *Interface*, Summer 2012, http://www.electrochem.org/dl/interface/sum/sum12/sum12_p037_044.pdf (accessed 4 November 2015)

[63] New components help lithium ion batteries take the heat. Nikkei Asian Review, March 24 2018. http://asia.nikkei.com/TechScience/Tech/Newcomponentshelplithiumionbatteriestaketheheat (last accessed 15 October 2015)

[64] Mixtures of ionic liquid – alkyl carbonates as electrolytes for safe lithium-ion batteries, L Lombardo, S Brutti, M Navarra, S Panero, P Reale, Journal of Power Sources, 2013, 227, 8–14

[65] A Lewandowski A Świderska-Mocek, Journal of Power Sources**,** 2009, 194, 601–609

[66] Quasi-Solid Electrolytes for High Temperature Lithium Ion Batteries, ACS Applied Materials and Interfaces, K Kalaga, M Rodrigues, H Gullapalli, G Babu, L Arava, P Ajayan, 2015, 7. 25777–25783

[67] Solid electrolytes: lithium ions on the fast track, C Masquelier, Nature Materials, 10, 649–650 (2011)

[68] Battco Ltd, http://www.batterycompany.co.uk/shop/sealed-lead-acid/?gclid=CLvF28e76sgCFYoEwwodGEIBwA (accessed 15 October 2015)

[69] Tracer high performance batteries, http://www.tracerpower.com/tracer-lifepo4-battery-packs.html, (accessed on 15 October 2015)

It has been argued [70] that the cycle life for LiFP batteries in both moderate and higher temperature climates is substantially longer than for VRLA battery types, but the origin of the data presented in that article is unclear and the authors themselves work for a Li-ion battery pack manufacturing company. Studies of degradation and aging (calendar and performance aging) of performance for individual LiFP cells (as opposed to battery packs) are becoming common,[71] and extend to designs geared towards high power output;[72] such studies have been sufficient for proposal of a number of cycle-life models.[73] There have also been a limited number of studies at elevated temperatures, again of individual cells.[74] Operating temperature is, however, a key issue affecting both battery pack design and the battery management system. There are currently a substantial number of published specifications indicating pack applicability at up to 65°C e.g. [75]. Persistence of high power performance at elevated temperatures needs, nonetheless, to be validated and/or challenged by independent study; cycle lifetimes need to be rigorously tested at high temperatures, with both cycle life and shelf life then being expected to be decrease substantially (as is the case for individual cells).

If greater cyclability for LiFP packs relative to VRLA packs is indeed true even at high temperatures, this could render these currently apparently more expensive pack technologies the more economical choice when considered over an extended period (fewer pack replacements). This could perhaps be true even without drastic reductions in the associated initial cost or could become more true if capital cost recovery could then be spread over a longer period (enabling lower periodic payments); this could also be true for LTO battery packs. The *current* cost of a LiFP pack, for instance, approaches (based on battery pack costs discussed above) ten times that for a VRLA system, but there is considerable scope for cost reduction after the initial research, development and deployment/introduction costs have been recovered for LiFP battery types. Similar considerations apply to the LTO battery type. For LiFP batteries there is reported good experience (e.g. in Ethiopia) for low power applications (as opposed to higher power solar cooking),[76] with multi-year warranties offered. Whether such performance would persist at

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[70] A comparison of lead acid to lithium-ion in stationary storage applications, G Albright, J Edie, S Al-Hallaj, on altenergymag.com (web magazine) http://www.altenergymag.com/content.php?post_type=1884 (last accessed 15 October 2015)

[71] Aging of a commercial graphite/$LiFePO_4$ cell, M Safari, C Delacourt, Journal of the Eelectrochemical Society, 2011, 2158, A1123-A1135 ; Calendar aging of a graphite/$LiFePO_4$ cell, M Kassem, J Bernard, R Revel, S Peliiser, F Ducloud, C Delacourt, Journal of Power Sources, 2012, 208, 296-305

[72] Cell degradation in commercial $LiFePO_4$ Cells with high-power and high-energy designs, M Dubarry, C Truchot, B Liaw, Journal of Power Sources, 2014, 258, 408-419

[73] Cycle-life model for graphite-$LiFePO_4$ cells, J Wang, P Liu, J Hicks-Garner, E Sherman, S Soukiazian, M Verbrugge, H Tataria, J Musser, P Finamore, Journal of Power Sources, 2011, 196, 3942-3948 ; Lithium iron phosphate based battery – Assessment of the aging parameters and development of cycle life model, N Omar , M Monem, Y Firouz, J Salminen, J Smekens, O Hegazy, H Gaulous, G Mulder, P van den Bossche, T Coosemans, J van Mierlo, Applied Energy, 2014, 113, 1575-1585

[74] As references 45 and 46. Effect of temperature on the ageing rate of Li ion battery operating above room temperature, F Leng, C Tan, M Pecht, Scientific Reports, 2015, 5, article number 12967 ; Capacity fade of Sony 18650 cells cycled at elevated temperatures: Part 1, Cycling Performance, P.Ramadass, B. Haran, R White, B Popov, Journal of Power Sources, 2001, 112, 606-613

[75] -20 +50°C http://www.victronenergy.de/upload/documents/Datasheet-12,8-Volt-lithium-iron-phosphate-batteries-DE.pdf ;
-15 +60 °C http://www.gaia-akku.com/fileadmin/user_upload/downloads/Handhabungshinweis_HP602030LFP-38Ah.122Wh.pdf
-20 +65 °C : http://www.easlithium.com/node/4 ;
-30 +60 °C http://shop.lipopower.de/LiNANOZ-Vision-V-LFP-12-5-5-Ah-128V-LiFePO4 ;
discharge -20 +60ºC, charge 0 +45ºC http://download.solarshop.net/uploads/Sony_LiFeP04.pdf ;
-30 +60 °C http://www.battcenter.de/RPower-LiFePO4-Lithium-Akku-12V-25-Ah-320-Wh--281.html
(all accessed 18 November 2015)

[76] http://www.fosera.com/ ; http://bennu-solar.com/fosera-pshs-7000/#.Vjc98itzvb8 ; https://www.lightingafrica.org/foseras-new-solar-tv-takes-home-outstanding-off-grid-appliance-award/ (accessed 3 Nov 2015)

high power (high C rate) and elevated temperatures for LTO or LiFP battery packs is not known.

Powering a basic solar electric cooker at 500 watts (500 W) would require an electrically connected and electronically controlled array of battery packs with the above characteristics. This simple conclusion follows directly from naïve calculation of the electrical current required at 12 V, the open circuit voltage of the *Powersonic* and *Tracer* packs above; using the simple equation *power = voltage x current* the necessary current is naively deduced to be 40 A (neglecting voltage loss at high current), which is in excess of the maximum current capabilities of those packs individually. Further, the electrical charge delivery required to cook for an hour at that current is then 40 A.h, in excess of the "capacity" of a single pack of either type. The way forward here would be to consider a pack configured to give a higher output voltage (say 48 V), with a consequently lower current requirement (giving more power per unit of charge transfer, more power per ampere hour); further, this would lower the required C rate and so protect the battery somewhat.

The 12 V packs of the preceding paragraph are engineered from lower voltage individual cells. Packs can certainly be engineered for still higher voltage operation (e.g. 24 or 48 V, as for LTO types used in electric vehicles), meaning that a lower current would indeed be needed. Such higher voltage packs are likely to be larger than the initially considered 12 V packs (for both VRLA and LiFP types) and are increasingly more electrically hazardous as voltage rating increases; it might be safer to adopt an array of 12 V packs as suggested above.

A battery management [77] and safety system for such an array of battery packs (and also of individual cells within LiFP packs) is likely to be mandatory, but the requirements could be less demanding than for older lithium ion technologies (e.g. lithium cobalt oxide types). The battery management system should, nonetheless, be geared to cope adequately with thermally harsh operating environments.

In summary, lithium ion battery battery types, packs and arrays suited even to solar electric cooking appear technically possible. There is, however, a shortage of key independent data for packs for this particular type of use and duty cycle, specifically for applications with extended periods of high current use (a deep discharge at very high C rate) at elevated temperatures. Further, there continue to be quite rapid advances in this area, with packs geared towards high temperature application shortly to be launched (see section 6). Dust in the environment is not an issue for sealed battery packs. At the current time the battery chemistries suitably developed for short term testing and implementation are the VRLA (lead acid), LTO and LiFP types. Other types under development may have promise but times from development to commercial market are typically 10 or more years.

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[77] A review on the key issues for lithium-ion battery management in electric vehicles, L Lu, X Han, J Li, J Hua, M Ouyang, Journal of Power Sources, 2013, 226, 272-288

SECTION 5

Insights from recent experience in the automobile industry

Much of the information in this area (in which battery pack designs are executed and applied) is proprietary but substantial information can be gleaned from the related press and other media.

Concerns relating to the life of lithium ion batteries in electric vehicles are evident and addressed in a press release (2013) from the American Chemical Society;[78] issues tackled include state of charge, charging protocol and temperature (with a clear statement that battery performance suffers above 86ºF, which is exceeded regularly in some areas of the USA in summer months). Such issues are of concern both to the OEM and the consumer end-user. Modes of necessary battery temperature control range from passive (all-electric Nissan Leaf [79]), to active air flow (all-electric Nissan NV200 van with the same power train as the Leaf [80]), to the liquid-cooled unit in the plug-in hybrid Chevrolet Volt [81,82].

Loss of battery capacity in the Nissan Leaf is an active concern (e.g. [83]), not least because of the limited range even of new all-electric vehicles. The Leaf is available with nominally 30 or 24 kW.h battery packs capable of delivering up to 90 kW, but the packs themselves are under continual development. US owners reported loss of capacity rapidly (well within warranty) in hot climates.[84] Concerns about the performance of lithium ion batteries have extended also into consumer electronics and related areas.[85] Such concerns are continuing to stimulate further development of such battery systems (with changes in cell chemistries) and changed battery pack designs.

The response of the battery industry and OEMs to concerns as they arise encourages optimism that future strategies will, in time, obviate current problems.

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[78] Understanding the life of lithium ion batteries in electric vehicles, http://www.acs.org/content/acs/en/pressroom/newsreleases/2013/april/understandingthelifeoflithiumionbatteriesinelectricvehicles.html

[79] 2015 Nissan Leaf Owner's Manual

[80] Could active thermal battery management in Nissan e-NV200 foreshadow future LEAFs? http://www.torquenews.com/2250/could-active-thermal-battery-management-nissan-e-nv200-foreshadow-future-leafs

[81] 2013 Chevrolet VOLT Owner Manual

[82] Chevy Volt Battery Cooling Systems and Algorithms, http://www.mychevroletvolt.com/chevyvoltbatterycoolingsystemsalgorithms

[83] Care and feeding of the Nissan LEAF battery, http://livingleaf.info/2012/07/care-and-feeding-of-the-nissan-leaf-battery/

[84] Nissan Leaf, https://en.wikipedia.org/wiki/Nissan_Leaf

[85] Operating Conditions Get Tougher On Li Ion Batteries, http://electronicdesign.com/power/operatingconditionsgettougherliionbatteries

SECTION 6

Recommendations

Lithium ion battery technology continues to be a rapidly evolving area. This report highlights that the proposed application is slightly ahead of the current ability of the technology to deliver, but also reports that future high power applications of such batteries in the developing world (at elevated temperatures) may well prove to be possible.

In the context of development of higher power solar electricity systems with potential for implementation in the developing world, the following five recommendations follow from the discussion above and could prove seminal.

Recommendation 1

A PROGRAMME OF EXPERIMENTATION

This should focus on full characterisation of the behaviour of LiFP battery packs (those current and those shortly to be introduced) and, for meaningful comparisons relative to an existing alternative battery pack approach, of VRLA battery packs, both with duty cycles appropriate to higher power delivery at elevated temperature, as would be required in solar electric cooking in, for instance, sub-Saharan Africa. This would be concerned both with individual cells and, most importantly, complete battery packs of the differing battery approaches.

In light of the perceived strengths of the LTO approach (discussed above), and provided that perceived increased inherent cost will not rule that type out, LTO battery packs should also be considered, at least initially, to compare their characteristics directly to the VRLA and LiFP types.

This approach could necessitate a project team establishing an interface with the HVM Battery Catapult. It should be noted that the matter is not as simple as substituting a VRLA battery pack with a LiFP pack of similar charge storage capacity. Power outputs from packs of similar charge storage capacities but of differing individual cell chemistry will differ, and it is the power output and its durability that are relevant to electric cooking.

Thorough safety testing under conditions of thermal abuse should be undertaken.

Recommendation 2

A LIFE-CYCLE-BASED TECHNO-ECONOMIC-ECOLOGICAL COMPARISON OF DIFFERENT ENERGY STORAGE OPTIONS

This is strongly recommended. Specifications for the battery management system for LiFP (and LTO) battery packs for such applications in “hot” countries can be developed from such a study. In addition the potential recycling of modern cell systems has to be investigated.

Recommendation 3
MAINTAIN A WATCHING BRIEF ON FUTURE BATTERY TECHNOLOGY DEVELOPMENTS

Li/S and Na ion battery types are under industrial development but currently well short of being able to enter the market competitively. Either of these battery types could have advantages relative to current lithium ion batteries.

Recommendation 4

DEVELOP AN INTERFACE BETWEEN A PROSPECTIVE SOLAR ELECTRIC COOKING DEVELOPMENT PROGRAMME AND BATTERY PACK MANUFACTURERS

This would enable cross-fertilisation of experience and ideas, and could one of a number of potential partners from industry.

Recommendation 5

CONSIDER THE POTENTIAL FOR EXTENDING CYCLE LIFE AND USEABLE ELECTRICAL ENERGY STORAGE PERFORMANCE BY INCORPORATION OF SUPERCAPACITOR COMPONENTS WHEN SEEKING PERSISTENT HIGH ELECTRICAL POWER OUTPUTS

Such extensions of cyclability and useable performance would be highly attractive but current supercapacitors are seen as being expensive. Possible ways forward to this end could be either (a) inclusion of supercapacitors (alongside individual battery cells) within future “electrical energy storage packs” or (b) by inclusion of one or more supercapacitor packs as discrete units within electrical energy storage arrays (battery packs + supercapacitor packs).   An interface with pack manufacturers would again be desirable here.   The cost of the next generation of supercapacitors could be substantially lowered if aqueous supercapacitor technology can be further developed and taken forward to marketability.