SMART VILLAGES
New thinking for off-grid communities worldwide

# Frontier Energy Storage Technologies and Global Energy Challenges

Smart Villages Initiative and University of Edinburgh

**Workshop Report 19**

May 2016

EDINBURGH, SCOTLAND

Key words:
Forward look workshop, Energy storage, Innovation, Batteries, Remote monitoring, Battery cost

## Smart Villages

We aim to provide policymakers, donors, and development agencies concerned with rural energy access with new insights on the real barriers to energy access in villages in developing countries—technological, financial and political—and how they can be overcome. We have chosen to focus on remote off-grid villages, where local solutions (home- or institution-based systems and mini-grids) are both more realistic and cheaper than national grid extension. Our concern is to ensure that energy access results in development and the creation of "smart villages" in which many of the benefits of life in modern societies are available to rural communities.

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## University of Edinburgh

The School of Social and Political Science is one of the largest Schools within the University of Edinburgh. Their international community of students and staff undertake a wide variety of learning, teaching, research and engagement activities. Their interdisciplinary focus cuts across traditional social scientific boundaries, creating a vibrant and stimulating environment in which to work and study.

## Publishing



The Smart Villages Initiative is being funded by the Cambridge Malaysian Education and Development Trust (CMEDT) and the Malaysian Commonwealth Studies Centre (MCSC) and through a grant from the Templeton World Charity Foundation (TWCF). The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the Cambridge Malaysian Education and Development Trust or the Templeton World Charity Foundation.



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## Summary

The University of Edinburgh together with the Smart Villages Initiative held a workshop at the Edinburgh Centre for Carbon Innovation on 11 May 2016. The workshop brought together social and physical scientists, industry representatives and entrepreneurs, energy and international development policy makers, and practitioners. The workshop provided an overview of new insights and research in battery storage. It also highlighted the social, environmental, and other impacts of large-scale battery deployments in developing countries in terms of end-of-life management and recycling.

An overview of the various technical aspects of battery research was provided by leading battery science academics from across the United Kingdom (UK), focussing on new types of battery electrodes and electrolytes that will provide various improvements on the current industry state of the art lithium ion batteries. There were subsequently talks from entrepreneurs actively trying to promote battery products, and battery recycling processes, in the developing world. This was followed by a description of a company making new lithium sulphur based batteries in the UK.

The social science perspective on energy storage solutions in the developing world presented a new way of looking at how batteries are used, from the beginning to the end of their product life. The UK Department for International Development (DfID) also outlined their plans to promote innovation and encourage better development outcomes from the use of battery technologies. A roadmap for battery technology improvement was presented that should advise policy makers and businesses on prospective developments over the next ten to twenty years.

The workshop was concluded by a discussion of opportunities for collaborating across disciplines to study energy storage, development, and recycling issues. The idea was mooted that more research could be focussed on designing batteries specifically with the needs of off-grid villagers in mind, and incorporating ideas from the circular economy into physical science research.

Key points from the workshop were that:

Progress in increasing battery performance will be incremental but significant over the next 10 years. Physical, chemical, and engineering research focuses on improving capacity, stability, safety and cost. Our understanding of materials systems at the atomic and molecular level will lead to gradual but substantial advances in all aspects of battery device design. Manufacturing learning curves, and scaling, and some manufacturing step changes introduced by the likes of the Tesla Gigafactory will provide major sources of cost reductions. Battery cost is predicted, by many in the industry, to reach below US$100 per kilowatt hour capacity by around 2020.

The price of lithium ion batteries will become favourable for off-grid solar home storage compared to the currently dominant lead acid battery at some point in the near future, although the cycle life of lead acid batteries will improve. Lithium sulfur batteries, and sodium-based batteries are promising technologies in the immediate to mid term (2–8 years) for increased capacity and lower price, respectively. Flow batteries are also promising for larger applications if their membrane price can be lowered as much as some predict.

Remote monitoring, as deployed by companies such as Bboxx and others, enables impressive improvements in battery lifetime and service and maintenance due to the ability to see in real time the state of charge and condition of the battery voltage and temperature.

For chemists working on new materials, trends in materials choice should be based on thorough analysis of social, economic, and physical con-

siderations as well as scientific considerations to avoid research being conducted based on “myths” or misconceptions.

Historically, batteries have not been designed to be recycled or easily repaired. This will become a much more important design consideration in future, and in particular for smart villages. For example, lithium recycling may become very important if lithium ion batteries take off. The infrastructure and procurement chain requirements of recycling of lead acid batteries, and in the future, other types of batteries, are in many cases too large for governments and businesses to achieve in the developing world. Engineers, entrepreneurs, and governments must work together to create new business models and new technical facilities that enable effective electronic waste management to avoid adverse environmental and health impacts.

## Introduction

More than a billion people worldwide still lack access to basic electrical services. As policymakers, entrepreneurs, and academics work to address the United Nations' Sustainable Energy for All (SE4ALL) goal by 2030, prominent technical solutions increasingly focus on decentralized connections to a renewable, intermittent energy source. Whether pico-solar lanterns, solar home systems, or larger solar, wind, or hybrid mini-grids, current technological solutions to challenges of global energy access must all include some form of energy storage for them to be useful. Yet energy storage remains a weak spot in policy, industry, and academic responses to global energy challenges.

Energy storage is recognised as a crucial factor in efforts to improve access to electricity.

The need for clean, affordable energy and transport is spurring research and development of battery and other storage technologies, and increased volumes of manufacturing are generating economies of scale that are anticipated to lead to substantial price reductions for future batteries. In the UK, DfID has identified battery storage at the household and community scale as a new and emerging frontier technology. Current innovations in energy storage include electro-chemical batteries (lead-acid, Li-ion, NaS, vanadium redox flow), flywheels, fuel cells, potential storage (pumped hydro), compressed air (CAES), thermal storage, magnetic storage, supercapacitors, and superconductors.

Different energy storage options come with costs and benefits. Some, like flywheels and lead acid batteries, provide high power at low cost but have a short lifetime. Others, like Li-ion batteries, are highly efficient and enjoy a long lifetime but remain prohibitively expensive for large-scale off-grid applications. If we are to promote a sustainable energy transition, our analysis must include the labour and environmental impacts of manufacturing and recycling.

As battery storage technologies are taken up in large scale in the coming years, end-of-life must also be a top priority. Particularly in the developing world, infrastructure for recycling and safe disposal of some of the toxic materials used in certain batteries can be lacking. This can have disastrous consequences. Lead acid batteries, for example, while low cost and high power, have a short lifetime. Used lead acid batteries are classified as hazardous waste under the Basel Convention. Informal or unregulated lead acid battery recycling is associated with various forms of toxic exposure, including the leaching of battery acid into soils and ground water, and the inhalation of lead particulates during the melting of lead plates.

With these opportunities and challenges in mind, the University of Edinburgh together with the Smart Villages Initiative held a workshop at the Edinburgh Centre for Carbon Innovation on 11th May 2016 to take a "forward look" into developments in battery technologies that could make a significant impact on off-grid electricity services in the developing world. The workshop brought together social and physical scientists, industry representatives and entrepreneurs, energy and international development policy makers, and practitioners. The workshop provided an overview of new insights and research in battery storage.

This report summarises the presentations and discussions at the workshop. Annex 1 presents the workshop agenda, and Annex 2 the list of participants.

## Scene setting, introduction to the workshop, and introduction to Smart Villages

Jamie Cross, University of Edinburgh, and John Holmes, Smart Villages Initiative

Jamie Cross welcomed participants on behalf of the University of Edinburgh. He gave a rationale for the event: to spark interdisciplinary collaboration between physical, material, and social scientists, and to engage across disciplines in order to support achievement of the United Nations Sustainable Development Goals, including Goal 7 on "Sustainable Energy for All".

John Holmes of the Smart Villages Initiative thanked Jamie Cross and the other organisers of the event. He then gave some background on issues of energy access in general and on how the workshop fitted in with the broader Smart Villages programme of engagement.

1.1 billion people live without access to energy. Three billion people cook on unclean stoves, leading to 4.3 million deaths per year. Sadly, these numbers aren't changing very quickly at the moment, so we need to work harder. This issue has been recognised by the Sustainable Development Goals (SDGs), particularly Goal 7—ensuring access to affordable, reliable, sustainable, and modern energy for all. But energy access is a key enabler for most of the other SDGs. If we want to reach the SDGs by 2030, we must make progress on energy access in a way that leads to development benefits.

The aim of the Smart Villages Initiative is to promote energy access as a catalyst for development, and look into the ways that energy access improves democratic engagement, health, welfare, productive enterprises, and education.

Smart villages will look different in different locations but will have a number of common features related to energy access as well as internet and communications technologies. Examples include access to modern health services, such as vaccines, light, and telemedicine. Smart villages will foster entrepreneurship in the provision and use of energy services, capture more of the agricultural value chain, spark new business development, foster strong rural/urban linkages, and develop more resilient communities that can withstand shocks.

The Smart Villages Initiative brings together the "front line" players—scientists, policymakers, entrepreneurs, villagers, NGOs, financers, and regulators—to discuss the barriers to energy access for development and how we can overcome them. The focus is on rural communities and local energy solutions, not the national grid. When the International Energy Agency looked at rural electricity access, they suggested that 70% of new connections would probably come from local solutions such as mini-grids and home solar systems.

The project team is based mostly at the Universities of Cambridge and Oxford. There are key partnerships with national science academies, and Practical Action, an international NGO. The project is funded by two charities: The Cambridge Malaysian Education and Development Trust (CMEDT) and the Templeton World Charity Foundation (TWCF).

In each of six regions (South and South East Asia, East and West Africa, Central and South America) there is a 12-18 month programme of engagement.

The programmes consist of workshops, capacity building events, media training workshops, competitions, and ongoing/cross cutting activities—such as communications through collections of essays, the website, webinars, research projects, and forward look workshops. Concluding events will be held by Smart Villages in June next year—including a big high level event in Brussels for the European Union, the United Nations, and the World Bank.

The idea of forward look workshops, like the Edinburgh workshop, is to bring together technical researchers from academia to discuss how what they are doing now might impact the world—especially off-grid villages—in the future.

In the Q&A, John Holmes gave more detail about the research projects Smart Villages is undertaking. The research project in Rwanda works with local partners and Practical Action to baseline certain metrics of village development just prior to a mini-grid being introduced to the village. This will show how mini-grid introduction, paired with initiatives for productive uses, play out.

The other project is in Borneo and seek to understand the local view towards information and communications technologies and how locals see what progress means.

# SESSION 1: CUTTING EDGE BATTERY RESEARCH FOR THE NEXT 10 YEARS

## Chemistry research for batteries in smart villages

Sian Dutton, University of Cambridge

Sian Dutton of the University of Cambridge gave an overview of lithium ion batteries and an introduction to her research on the next generation of battery materials and devices. The goal of her research group is to develop new and improved materials and to understand why they work (or do not work). The research relies on controlling the materials that they put into a device, and their arrangement in space. The group then observes the physical properties that impact the material performance of the battery device. The focus is on ceramic materials, using solid-state synthesis. Oxides and carbonates are used to control the reaction conditions along with varying reaction times and temperatures to change what happens to the materials.

They study the physical properties using a variety of techniques, such as X-ray diffraction (XRD), superconducting quantum interference devices (SQUIDs), and standard electrical battery testing. The group's focus is on the fundamental properties of materials—rather than how you would actually build a commercial battery.

The use of rechargeable batteries is ubiquitous, for example, they are in laptops, phones, and electric vehicles. Newer applications will include flexible batteries for monitoring heart rate, and batteries for grid storage. All of these applications require batteries with different qualities. For instance, for wearable batteries, safety is important as well as weight and size. For off-grid applications, cost is the most important as well as reliability.

Sian Dutton briefly explained the basics of how batteries work. Batteries are based on a rechargeable ion system—ions (charged particles) are transported through an electrolyte (electronically insulating material), which results in electrons then moving through a circuit. In rechargeable batteries, one can move ions and electrons through the circuit in both directions many times.

An aspect of Sian Dutton's research looks at solid-state electrolytes. Compared to the standard liquid electrolytes, solid-state electrolytes have the advantage of being capable of making much smaller batteries with higher energy densities, but there are often more safety concerns. Her group is also looking at new types of electrodes (electrodes are the interface materials between the ion/electrolyte portion of the battery, and the electronic wire circuit the battery is connected to).

She outlined a collaboration she has that involves working on magnesium ion batteries. These are batteries that use magnesium as the moving ions instead of, for instance, lithium in a lithium ion battery.

Magnesium ions are divalent, meaning that each ion can generate two charges, compared to monovalent ions that only generate one charge per ion (as in lithium-based batteries). Another advantage of these batteries is that one can make them with magnesium anodes (one of the electrodes), which can lead to less risk of short-circuiting the battery. Magnesium is also much more abundant than lithium. The first battery of this type was built in 2000. Currently, their capacity is about half that of lithium ion batteries, and they operate at lower voltage, but can operate over many cycles. There are still problems that have so far hampered progress towards commercial magnesium ion batteries. They include the need to redesign the system based on the new materials, and difficulties in testing the new systems. The voltage will also need to be raised to be competitive.

Sian Dutton explained the criteria for developing improved electrodes. She is developing them by studying a range of possible new materials that are theoretically comparable to, or better than, those in lithium based systems.

Often, making an electrode for the new magnesium-based system along similar lines to the way electrodes are made in lithium ion batteries is not sufficient to make an effective system. A direct magnesium analogue often does not exist, so researchers must look for wholly new materials. Such materials include $MgMnB_2O_5$, which has a theoretically high energy density. Experiments on this material have shown some promising results, but also found significant problems with material degradation.

Sian Dutton concluded that there is still a long way to go with magnesium based systems, but they show many intrinsic advantages if the system can be optimised.

In the Q&A, a participant asked if there are environmental issues with any of her systems. Sian Dutton responded that this depends on the electrolyte, as if the electrolyte is a liquid it can get into the environment more easily.

## Future battery chemistries—the role of sodium

Robert Armstrong, Saint Andrews University

Robert Armstrong described his work on sodium ion batteries. He outlined the properties of sodium-based batteries that make them attractive to study and potentially commercialise.

Sodium, like lithium, gives rise to a monovalent (single charge ion) battery system, which makes a lot of the chemistry similar to lithium ion battery-based systems. Sodium is cheap. It is a fraction of the cost of lithium, and this is important for grid scale applications. The main difference between lithium and sodium comes from the difference in the ionic radii.

Lithium works well, but it is important to look for alternatives. Lithium is not distributed across the planet—with most of the world's supply in the salt flats of the Andes. If there is a large peak in demand due to electric vehicles, for instance, the supply could impose constraints. Sodium is much more abundant, readily extractable, and spread throughout world. But sodium batteries have lower voltages, are heavier, and have lower energy densities than lithium batteries.

For sodium batteries, another cost advantage is that the negative anode can be made with aluminium instead of the expensive copper plate that covers the graphite electrode in lithium batteries. Rob Armstrong also went over some of the different options for making the negative electrode itself in a sodium battery such as using organics or different alloys.

For the positive electrodes, sodium ion batteries use similar classes of materials to lithium ion batteries. Rob Armstrong has studied the properties of polyanions, like the common vanadium phosphate polyanion, which have high voltages in a sodium system. But the system also allows the use of iron or manganese based positive electrodes, which are interesting to study, although they have stability issues. A lot of the work his team has done has been on layered compounds of these iron or manganese electrodes. His team has been able to add dopants to the manganese system in order to get rid of unwanted material phase transitions in order to increase battery performance. In terms of cyclability, the sodium systems can discharge quickly but are slow to charge up.

Rob Armstrong concluded by noting that sodium and lithium ions are similar, but there are attractive and unique properties for sodium batteries. They can be low cost, and their performance could rival lithium ion batteries.

In the Q&A, it was noted that putting a timeline on commercialisation is difficult, but there are prototypes already available.

## Ions that can hop, skip, and jump: Lithium conduction in disordered, crystalline solids

Ed Cussen, University of Strathclyde

Ed Cussen presented work on fast lithium conducting solids in which the mobility of Li+ could make for improved lithium ion batteries compared to current technology which uses liquid electrolytes. In addition to synthesising new materials, he uses a combination of neutron diffraction, impedance analysis, and solid state nuclear magnetic resonance imaging (NMR) to build a full picture of the origins and properties of lithium transport through these structures.

The conventional model of a solid crystal portrays atoms as immobilised on well-defined positions in space. This regular structure is evident in the highly defined order and symmetries of the diffraction patterns obtained from crystalline materials. However, there are a number of crystalline solids where a subset of the atoms shows a high degree of mobility. In some of these phases, ions are able to move at speeds approaching those in molten salts or solutions. This ion mobility may be associated with very substantial disorder in the lattice and dramatic changes in the diffraction properties of the crystal. The best ionic conduction in oxides is shown in lithium lanthanum titanate ($LiLaTiO_3$). The scientific literature still has a lively debate going on how this conduction works. Ed Cussen noted that this is quite "forward-looking research". It took lithium iron phosphate 10-15 years of development for widespread use, and this is the timescale that his research is working on.

There are some advantages to liquid electrolytes—they are easy to process, and if they expand or contract, they can still fit into the battery system. A major problem is that they are more reactive and can catch fire much more easily than solid electrolytes. This is why Ed Cussen's group focuses on finding new materials that have a high lithium conductivity but are intrinsically stable to create a solid state battery.

Ed Cussen outlined some work he and his group had done to study some new types of materials to achieve the goal of a solid state battery. Garnets are "neosilicates" with a specific chemical formula. To form a garnet that will be useful in a battery, one must normally heat some oxides and carbonates for 1.5 days at 1230 degrees elcius. Researchers at Strathclyde have been able to produce these materials using microwaves in one hour at only 1000 degrees Celsius. Rob Armstrong showed work in these materials proving that $Li^+$ is the only mobile ion. He also showed other details about the transport of lithium in a detailed, disordered, and dynamic energy landscape.

Another candidate for different electrolytes is that of an amorphous or gel like material such as lithium sulfate. In its crystalline form it is not very effective, but shows interesting properties when heated up. Above a certain temperature, the material becomes amorphous, and lithium ion movement is observed. The group has also looked at lithium conduction in alkali metal borohydrides, which have shown conduction at just over 100 degrees Celsius. A number of approaches have been trialed to lower this temperature to room temperature.

In summary, Ed Cussen indicated that there are many challenges to achieving a commercial solid state lithium based battery: there is a need to stabilise interfaces, work on processing, and focus on safety. It is also necessary to be able to make materials in large enough amounts to achieve commercialisation—so this is a consideration in research.

## SESSION 2: FROM BATTERY RESEARCH TO APPLICATION IN THE DEVELOPING WORLD

### Lead acid battery recycling in the developing world

George Lane, Citrecycle

George Lane is the chief technology officer of the company Citrecycle, which is developing a new process for recycling lead acid batteries. He discussed the problems of lead acid battery recycling in the developing world, and Citrecycle's proposed solution to these problems.

The current structure of the lead acid battery recycling industry in many developing nations is as follows. Lead acid batteries are used in many places— cars, off grid energy storage, etc. These batteries get collected by waste pickers, and middlemen sell the batteries to informal sector recyclers and some formal recyclers. The formal sector is large scale with industrial processes operating at the necessary high temperatures, while the informal sector basically amounts to people in their back yard chopping up the batteries and heating them themselves. Both produce metallic lead that is sold to battery manufacturers who produce new batteries.

Citrecycle wants to develop a new process. In this process, they would buy used batteries from the same supply chain—but would use clean, green, low-energy processing techniques to recycle the batteries. It would separate the components, process the lead paste (60% of lead in batteries), resulting in new lead feedstock. The goal is to also include the informal recycling sector into their model, in such a way that the problems of the informal sector are solved. These problems are severe. Lead pollution is the largest industrial pollutant problem in world. In Mexico, half of all children have lead poisoning; half of the Indian population tested positive for lead poisoning also. Lead biochemically behaves like calcium, but it inhibits proteins that calcium activates for learning.

There are three specific challenges for the company: it needs geographic reach (distribution centers need to be spread throughout a region); it needs to absorb the informal recycling sector; and it needs to be profitable. To achieve reach, it needs to secure supplies of batteries while keeping requirements for infrastructure low. To absorb the informal sector, it needs to pay more for used batteries than is currently the case and provide employment in plants and in the supply network. The company would also need to help with education on the dangers of informal lead recycling. To achieve profitability, it is predicted that a series of distributed plants of Citrecycle's design would need to recycle around 20 tonnes of batteries per day.

The team is currently looking at India to do the first pilot project. There is a government mandate requiring lead acid manufactures to recycle 90% of batteries, but the country is currently stuck at 40%. The company is currently raising money to go into laboratory work to understand some chemical engineering questions. The pilot plant is hoped to begin by early 2017, and the team is actively looking for partners to do this with in India.

In the Q&A, there were further questions on the numbers given in the model George Lane proposed. He clarified that 20 tonnes of batteries per day is a number provided by roughly five million of the average Indian population. He also noted that Citrecycle's more distributed system could be tailored to different environments.

### Bboxx's smart solar platform

Karla Cervantes and Ashley Graelish, Bboxx

Ashley Graelish is the leader in product development at BBoxx, and Karla Cervantes is working with a car battery system and conducting research into batteries. Bboxx sells solar home systems across the world, with a focus on East Africa. They sell to 13,000 customers per day, with most units in Rwanda and Kenya. The core component of the "Bboxx home" product is its battery, which has remote monitoring built in. Each product is connected to a geosynchronous orbital (GSO) satellite network, which sends data back to the company on how the unit is being used, what the health of the battery is, temperature, and energy use patterns. This is very useful for monitoring the battery to replace it before it degrades too much, meaning there is no system downtime.

Ashley Graelish showed some of the data collected on the batteries—temperature, voltage, and current data of the 12-volt lead acid batteries.

Using lead acid still makes sense in terms of cost, but Bboxx may use lithium ion at some point. Lead acid batteries have shortened lifetimes if they are fully discharged multiple times.

For their estimations of the instantaneous state of health of the batteries, Bboxx looks at the charging and discharging of individual batteries and compares their performance to calculated performance curves. They categorise users into different groups: heavy users, for example, a customer in Kenya who has a bar with TV and radio (both are on all day), or light users, who only use the system for lighting and mobile phone charging.

Bboxx also cares very much about the batteries' end of life processing and recycling. Once the battery is dead, someone collects it, removes combustible materials, chops into the cells, heats to liquefy metal, forms a lead ingot, and reuses the materials for new batteries. The company needs a new recycling model, though. Right now, they give batteries to a third party to be recycled, but they want to look into the market potential of recycling, and if Bboxx grows, they must consider the increased volume of batteries, and must bring solutions that do not create environmental problems.

## Session 3: Perspectives from industry, the social sciences, and government

### Li-S batteries for energy storage applications

David Ainsworth, Oxis Energy

Oxis Energy is a SME based in Oxfordshire working on lithium sulfur technology for batteries. It has expanded rapidly in the last 50 years, with battery research facilities and a patent portfolio on which its business model is based on licensing.

David Ainsworth described the lithium-sulfur (Li-S) based batteries that the company works on. Li-S batteries have a high gravimetric energy (i.e., they can store a large amount of energy in a light weight device). They have good safety properties. Sulfur is a cheap material, so the prospects for long term use look good. The company produces lithium sulfur (Li-S) pouch cells to build into batteries and has a 3 kWh battery for larger storage applications, as well as smaller batteries.

If you take apart a Li-S battery, it looks similar to a lithium ion battery cell—but the chemistry is very different. The sulfur electrode is interspersed with conductive carbon. There are intermediate species (soluble $Li_2S_x$) that make the working mechanism of the cells more complex.

Oxis now has a pilot production facility. It is targeting a variety of different sectors. The technology is long life—batteries have demonstrated 1500 cycles. The applications targeted are grid storage and light electric vehicles. They also make high energy density cells for space or military applications, but these have shorter lifetimes.

The commercial products still need to improve further, however, and materials research is the base of this improvement. Oxis energy has a large team of engineers and scientists to look at all components of the battery cells—anodes, cathodes, and electrolytes. David Ainsworth talked about the key considerations for static energy storage. Cost modeling says that the batteries should cost around US$200 per kilowatt hour with a target of 2000 cycles.

In terms of recyclability, there are no transition metals, which is an advantage, but only lithium metal has any real value in the material construction of a cell. The energy density can be improved in a cell by focusing on improving the electrolyte (as this accounts for 50% of the mass of a cell). Cycle life improvements can be made by protecting the lithium-metal anodes or by coating the lithium anodes with a polymer film to reduce reactivity.

Oxis' concept for static energy storage consists of a 3kWh rack-mounted system which will be modular (the rack can be filled with 50kWh of capacity). They are looking for collaborations to build the technology into a larger system.

David Ainsworth concluded by saying that the outlook for LiS looks good due to the low cost and long cycle life. But lithium ion batteries took ten years to get into mainstream applications, and another ten years to get into larger scale applications.

In the Q&A session, it was noted that for static energy storage applications, one would need to make millions of battery units to become cost effective. Production of Li-S is very similar to Li ion production, but with some tweaks, the biggest difference comes from the metallic lithium anode in the Li-S system.

### Batteries and energy storage in social sciences

Jamie Cross, Edinburgh University

Jamie Cross' talk discussed what the social science disciplines may be able to say about batteries. He argued that batteries are often seen as a black box:

they provide energy, but people do not know much about where they come from, how they are disposed of, or how they are used. The social sciences can help to open the black box, by raising questions relating to practice, demand, value, waste, and justice.

The social sciences reflect on what people use energy for and how this impacts issues like what types of batteries are common or when electricity is used. Batteries have a mobile property in that they can be moved and carried over long distances to be traded, exchanged, or recharged. The value of batteries is often discussed in terms of lifecycle analysis and carbon footprints, but social scientists should look beyond this and examine the value chain, including the sites of production and disposal. This raises questions of what social or economic value the design, manufacture, use, and disposal creates, and for whom.

Waste from batteries is an important issue, and social scientists should learn more about informal and formal recycling networks and informal economies. There are also issues of justice, which may be framed as questions of where things reach, and who wins and loses from distribution and use.

Jamie Cross closed by raising the question of how social scientists could collaborate on research with scientists.

## Energy storage and universal access to modern energy services

Alistair Wray, UK Department of International Development (DfID)

Alistair Wray discussed how Sustainable Development Goal 7 calls for action to provide sustainable energy for all. To attain sustainable energy for all, we must expand national and regional grids and develop mini-grid and off-grid sources of energy as well as focusing on renewable sources of energy rather than fossil fuels.

Solar energy, in the form of photovoltaics, is becoming an important option for achieving sustainable energy for mini-grid and off-grid solutions as the price of photovoltaics is falling and desire is increasing. We need to push more for productive uses of energy and develop initiatives with SMEs to use energy for business purposes as well as connectivity uses like TV or phone charging.

DFID so far has supported this area by focusing on sparking innovation through challenge funds and prizes offered toward specific challenges. It has not focused much on clean cooking, though research shows that improved biomass cook stoves are insufficient to gain many of the health benefits—and so a shift toward LPG is needed to improve health.

DFID will to continue to look at expanding renewable energy, developing people's skills and capacity, and exploring new ways to help communities obtain sustainable energy. Affordable energy storage is needed to enable effective use of renewable energy, and challenges remain in respect of cost and being able to meet power requirements.

DFID projects include the Energy Africa Initiative, which supports projects that aim to sell energy or solar panels at the same price households would spend on kerosene or coal each week. It hopes to catalyse business development in villages. Another project is the Transforming Energy Access (TEA) programme, which seeks to improve renewable energy sources, finance company investments in renewables, and spark innovation.

## Energy storage technologies for climate change mitigation

Sheridan Few, Grantham Institute

Sheridan Few from the Grantham Institute is working to bring technical research on climate change and energy together with policy advice. He gave an overview of his study on where energy storage technologies are going in the next 10-20 years and what policies should be in place to encourage their development.

The study involved technology selection, expert elicitation, and energy system modeling. It was supported by the creation of an infographic to aid in the appropriate selection of energy storage technologies for specific needs.

Sheridan Few highlighted a specific case study from 2011 that gave an indication of where diesel or solar PV is more cost effective for electrification. He also mentioned a study by Philip Sandwell that modeled the optimum design of photovoltaic-diesel hybrid mini-grids incorporating storage based on carbon intensity and cost.

Sheridan Few asked a series of experts from academia and industry, "on an off-grid scale, which three electricity storage technologies could be the least expensive by 2030 for balancing intermittent renewables?". Most went for electrochemical energy storage, but there was a wide range of responses.

He looked at the timescales for innovation for various technologies. Examples showed that lithium ion batteries had a shorter innovation lead-in time than other technologies, around 15 years, but energy generating technologies had some of the longest "lead-in times".

A summary of different technologies for off-grid battery storage noted that lead acid batteries are the incumbent technology for most systems. Lithium ion batteries are interesting due to costs reducing rapidly, intensive R&D, and a push from private industry.

With regard to cost reductions to be expected in the coming years, learning rates—"learning by doing"—decrease by 10% or so each year, meaning that the rate of improvement in price will gradually decrease. Bottom-up technology assessments should also play a key role in determining what the final price of systems will be. An example of lithium ion technology is electric vehicle batteries. There is a general trend of decreasing costs, but people still do not really predict how innovations will take place. Possible developments can come from cell materials, labour reductions, and scaling up production.

Most experts think in 2020, batteries will have very similar chemistries to now, but perhaps by 2030 there will be novel chemistries. There is a lot of potential and need for lifecycle and technical improvements.

## Session 4: Keynote: Trends in battery research and implications for end-of-product-life considerations

Clare Grey, University of Cambridge

Clare Grey from the University of Cambridge gave a keynote address on current progress and future trends in battery technology as they relate to off-grid villages.

Storage of electricity is needed over a wide range of capacities and timescales. The cost of the battery per kilowatt hour of battery capacity is the important metric for grid or electric vehicle batteries. Tesla claims there will be sharp drops in the price of lithium ion batteries by 2020—down to US$100 per kilowatt hour. General Motors says this price will be reached by 2022.

The Tesla Gigafactory will have solar panels on its roof so that it will produce batteries in a more sustainable way—the lifecycle analysis will be unique for these batteries. Today's battery assembly process requires 400 kWh of energy to make a battery which delivers 1 kWh of energy. This releases 75 kg of $CO_2$.

The ways to reduce cost in batteries are: cheaper materials, thicker electrodes (this reduces the "separator material" cost), increased capacity and longevity, and creation of a second-hand market.

Clare Grey outlined some areas in materials research for improving performance and reducing cost. The cathode materials that are used currently—manganese spinels—have good electronic conductivity and high power density, but low capacity. Lithium cobalt oxide is another contender, but it is expensive. This can be balanced by adding in manganese oxide, which is cheaper, but this reduces capacity.

Batteries based on lithium iron phosphate ($LiFePO_4$) are leading contenders to dominate the storage market. One can also use silicates, borates, and sulfates to achieve similar results. These systems have moderate capacities, are safe, and operate at low voltages. They can be made with cheaper materials, but this leads to higher production costs.

Intercalation materials—the materials through which the mobile ions travel—are the subject of much research. One needs a material that retains integrity when you pull lithium in and out of it, which is a challenge. Another area of research showing promise is high capacity anodes. Researchers have achieved capacities using silicon-based anodes that are 10 times higher than those of the standard carbon- based anodes.

Clare Grey's own work involves probing local environments around the atomic nuclei of materials inside the batteries. She has looked at the potential for lithium silicide to be used as a material that would reduce the amount of electrolyte needed in a battery. Her group has been able to monitor in real time the formation of a coating that passivates the anode in these batteries, to work out how to utilise this passivating reaction effectively. A lot of work has been done to push silicon as a new material in batteries for the past 10 years. The goal is not to use the entire capacity of silicon but to use part of it.

Clare Grey summarised some current directions in the battery field:

1. Batteries that are currently designed to be small for portable electronics may be scaled up to make large, grid-scale devices. The separator between the electrodes for lithium ion batteries in portable electronics is only 50-100 microns in thickness. To store more energy, one needs a thicker separator, but one cannot just expand the separator because lithium ions still need to make it all the way through

the separator material. Safety is another issue with scaling up.

2. Sodium ion batteries are closest to market penetration out of the new technology types that are talked about. Some problems people expected for sodium have not materialised—and costs are better since you do not need copper in these batteries.

3. The jury is still out on solid-state batteries. They represent the ultimate in safety as you remove the electrolyte, but much is unknown.

4. Lithium air batteries are an interesting technology as they have the potential to rival gasoline in energy density.

5. Lithium usage is predicted to explode. Currently, there is actually a large amount of lithium going into concrete, but batteries will take up a much greater share very soon. Opinion differs on whether there will be a lithium shortage issue or not. Does this mean that we should pursue non-lithium technologies? What will be the price increases associated with changing supply and demand?

6. If you really want to reduce costs, organic electrolytes would be an excellent candidate. Aqueous batteries are also intriguing. Aquion is an example of a company that makes an aqueous sodium manganese oxide battery, which has a voltage of 1.5 volts. These types of batteries may not be cheaper because of their high salt concentrations, but they may be safer.

7. Redox flow batteries are promising. It is important to try and see where the cost is coming from in these systems. Much of the cost comes from the membrane. Despite lots of research, there have not been many reductions in membrane cost, yet it has been modelled that the membrane cost will drop by a factor of 10 in the next few years. A challenge for aqueous redox flow systems is to get more redox centers per volume.

8. A new and innovative avenue is looking at sustainable binding materials. There is a proposal to use algae as binders.

Clare Grey stressed that it is very important to understand how things work in situ and also how they fail: this is vital for increasing cell stability and decreasing costs. There is a need for more diagnostic methods for batteries. An example is putting a fiber optic in a pouch cell to look at strain inside the battery during operation.

Supercapacitors are also another key means of energy storage. These are made with porous materials with organic or aqueous electrolytes (porous carbon materials are traditionally used). The challenge for supercapacitors is increasing energy density.

What will the future of battery progress look like? Clare Grey thinks there will be new chemistry progress that is incremental but significant.

The Q&A session focused on the potential for flow batteries to be used in off-grid villages, and what their potential maintenance issues be. This is a difficult question to answer. Something that was brought up was that the pump as well as the membrane in a flow battery might become limiting factors for scaling up the size of the system.

## Session 5: Discussion

Jamie Cross initiated the discussion with a consideration of potential funding opportunities for work on energy storage and recycling for rural communities in the developing world. One potential source of funds is the Global Challenges Research Fund, which has a budget of £1.5 billion over five years. DfID have an interest in this research fund particularly as it relates to supporting issues of concern in Overseas Development Assistance. Sub-Saharan Africa is the region of most interest to DfID. The specific interests of individual research councils were discussed. EPSRC, in particular, is likely to be interested in research relating to off-grid electricity systems and battery storage. It was concluded that there are potentially significant amounts of research funding available in the UK currently. We may expect to see some rapid response calls, requiring proposals in 3 to 4 weeks, over coming months.

Typically, not much attention is given by researchers to the sources of materials and the local impacts of mining when they are developing new technologies. A more systematic approach would be beneficial. Quite often, "myths" drive trends in research. For example, there was much interest in nickel-based systems because nickel was considered to be cheap (but became expensive), and everyone stopped working on vanadium because it is toxic. However, the view was expressed that if you are undertaking fundamental research to look for step changes in technology, you should allow yourself a free choice of materials.

The circular economy is a powerful concept and may usefully inform battery research activities. Historically, batteries have not been designed to be recycled. This will become a much more important design consideration in future. For example, lithium recycling may become very important if lithium ion batteries take off in a big way.

If it were possible to manufacture batteries locally, the recycling process could be included as the front end of the manufacturing plant. While such manufacturing and recycling is unlikely to be undertaken at the village level, it may be possible at regional centres. In pay-for-services business models for solar lights and solar home systems ownership of the battery remains with the company providing a more focused responsibility for recycling.

Specific energy uses such as milling, refrigeration, and water pumping may be powered by their own solar panel leading to the consideration that a dedicated battery might be designed according to the specific use. However, that would hinder cost reductions through economies of scale.

## Annex 1: Agenda

**Tuesday 10 May:**

19.30 Dinner, Mother India's Café, 3-5 Infirmary St, Old Town, Edinburgh EH1 1LT

**Wednesday 11 May:**

09.00 Arrival and Registration, Edinburgh Centre for Carbon Innovation

**Scene Setting and introduction to Smart Villages**

09.30 Jamie Cross and John Holmes, The University of Edinburgh and The Smart Villages Initiative

**Session 1: Cutting-edge battery research for the next 10 years**

09.50 Chemistry research for batteries in smart villages, Sian Dutton, University of Cambridge

10.10 Future battery chemistries—the role of sodium, Rob Armstrong, Saint Andrews University

10.30 Ions that can hop, skip, and jump: Lithium conduction in disordered, crystalline solids, Edmund Cussen, Strathclyde University

**Session 2: From battery research to application in the developing world**

10.50 Lead acid battery recycling in the developing world George Lane, Citrecycle

11.10 Bboxx's smart solar platform Karla Cervantes and Ashley Graelish, Bboxx

11.30 Coffee

**Session 3: Perspectives from industry, the social sciences, and government**

11.50 Li-S batteries for energy storage applications, David Ainsworth, Oxis Energy

12.10 Batteries and energy storage in social sciences, Jamie Cross, University of Edinburgh

12.40 Energy storage and universal access to modern energy services, Alistair Wray, Department for International Development

13.10 Lunch

14.00 Energy Storage Technologies for Climate Change Mitigation, Sheridan Few, Grantham Institute

**Session 4: Keynote: Trends in battery research and implications for end-of-product-life considerations**

14.00 Clare Grey, University of Cambridge

**Session 5: Discussion session**

14.45 Group Breakouts, facilitated by Jamie Cross

15.30 Coffee

16.00 Discussion conclusion

16.45 Reception and conclusion

## ANNEX 2: PARTICIPANTS

| | | |
|---|---|---|
| David | Ainsworth | Oxis Energy |
| Andrew | Aldritch | Green Angel Syndicate |
| Ilone | Amos | The Scotsman |
| Hope | Bretscher | University of Edinburgh |
| Kirsten | Campbell | University of Edinburgh |
| Karla | Cervantes | Bboxx |
| Jamie | Cross | University of Edinburgh |
| Edmund | Cussen | University of Strathclyde |
| Peter | Davison | University of Newcastle |
| Sandy | Evans | Smart Villages |
| Kristen | Fedeler | University of Edinburgh |
| Sheridan | Few | Grantham Institute |
| John | Holmes | Smart Villages |
| Vasant | Kumar | University of Cambridge |
| George | Lane | Citrecycle |
| Lukas | Lokoshek | MeshPower |
| Gemma | May | DfID |
| Andy | Mead | Firefly |
| Mike | Price | Smart Villages |
| Emilio | Soberon | University of Edinburgh |
| Alistair | Wray | DfID |

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SMART VILLAGES
New thinking for off-grid communities worldwide

The Smart Villages initiative is being funded by the Cambridge Malaysian Education and Development Trust (CMEDT) and the Malaysian Commonwealth Studies Centre (MCSC) and through a grant from the Templeton World Charity Foundation (TWCF). The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the Cambridge Malaysian Education and Development Trust or the Templeton World Charity Foundation.



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