SMART VILLAGES
New thinking for off-grid communities worldwide

Smart Villages Forward Look Workshop: Potential Breakthroughs in the Use of Energy in Off-Grid Villages

Workshop Report 14

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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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Summary

The 'forward look' workshop on potential breakthroughs in the use of energy in off-grid villages" was held in Churchill College, University of Cambridge on 18 December 2015. An introduction to the workshop's aims and to the Smart Villages Initiative was followed by an introduction to the concept of "distributed manufacturing" for rural villages and accounts of new technologies for low-cost refrigeration and solar pumps.

The next session focused on the value that communities place on services in Kenya, an overview of low powered direct current (DC) motors, and a discussion of the merits of DC versus AC appliances and home systems for remote rural households in developing countries. After lunch, there were talks on 3D printing for rural villages and increased farming precision enabled by technology in the United Kingdom and developing countries. The final session consisted of a series of four quick-fire talks and discussions on a diverse range of topics: a new concept for low flow tidal power generation, an overview of student entrepreneurial programmes with the Cambridge Development Initiative, a study on methods for gauging what value end users in rural villages place on services, and an overview of the concept of frugal innovation, with examples from India and the developing world. To conclude the workshop, participants discussed their views on the key messages to express to donors and policymakers.

Key findings may be summarised as follows:

- There is a need to better understand the market for people currently living off-grid in order to predict future trends. What do they truly value? What local enterprises and powered equipment will be of the most utility to a community? These questions can be better answered through improved metrics and further study.

- Distributed manufacturing can have potential for rural communities in certain contexts in the developing world. Tariff structures for importing of goods and component parts should be designed such that local manufacturing is not unfairly discouraged.

Tom Smith, Thermofluidics Ltd. demonstrates a low cost thermally-powered pump

- Further investigation is needed into the issue of low-power consuming DC appliances for off-grid markets. As an increasing number of these products are produced, further attention should be given to safety issues, improving electrical standards, and defining an optimally efficient home system. Research should be undertaken on other options such as using a "quasi-square wave" transmission form rather than standard alternating or direct current transmission.

- Investment is needed in new and low-cost technologies relevant to off-grid development, such as new refrigeration or solar water pumping technologies. However, there is tension between between open source design (and local manufacturing and assembly) and the protection of intellectual property in order to encourage investment.

- "Proving factories" as used in the automotive industry could help speed the scale up of new technologies. Such proving factories typically employ 15 to 20 people: they take ideas and test out how they might be scaled by examining issues like sourcing components, required accuracy, and design for market.

- The path to commercialisation of potentially important technologies, such as improved, cheaper brushless DC motors, is difficult. Governments and investors can aid the path to mass production.

- It is important to be aware of potential game-changing technologies like 3D printing, which is rapidly improving in cost and quality and will likely have a role to play for remote communities in the near future.

- Crowdsourcing and access to new data acquisition technologies to improve agriculture and help de-risk financial investments can provide substantial benefit for developing communities. Local governments should collect data and provide detailed agricultural, demographic, and other types of datasets to local businesses and investors.

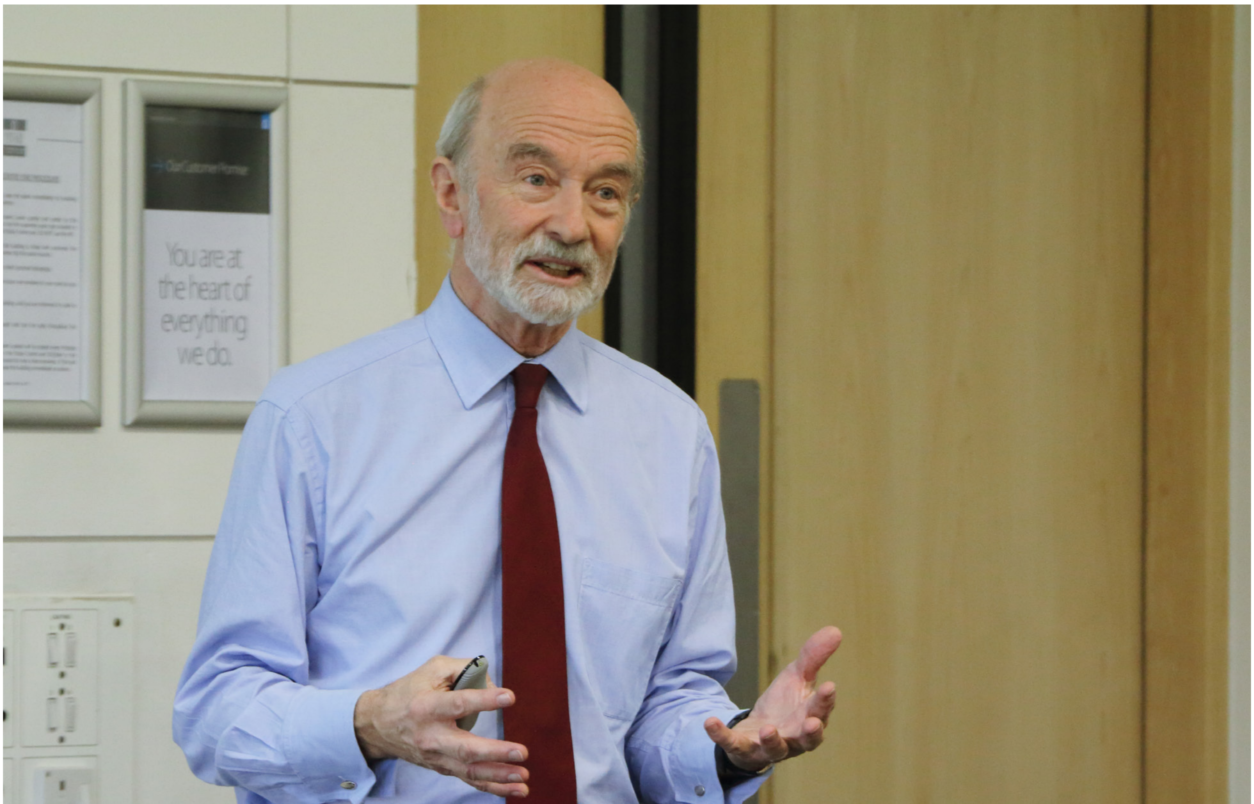
Workshop participants

Introduction

The Smart Villages Initiative aims to advance sustainable energy provision for development in off-grid villages in Africa, Asia, and Latin America and the Caribbean. As part of its on-going series of engagements across the globe, the Initiative is running a series of "forward look" workshops, which aim to take a more detailed look at technical and scientific developments relevant to rural electrification that might have real-world impact in the coming 5-15 years.

In order to achieve significant enhancements in the quality of life of the rural poor, energy access is a crucial factor. Equally though, the ways in which this energy is used in these communities is also critical. The purpose of the workshop was to bring together leading UK researchers and practitioners to discuss emerging technologies relevant to the "productive use of energy" in rural communities in developing countries. Answering questions such as, "what advances in energy-efficient appliances will have an impact on the off-grid market?" and "how might new distributed energy sources affect and influence new productive enterprises?" can help achieve the Sustainable Development Goals, including Goal 7 on universal energy access for all.

The workshop was held in Cambridge, United Kingdom, on 18 December 2015. This report presents summaries of presentations and discussions at the workshop that involved an interdisciplinary group of experts from across the United Kingdom from academia, industry, business, and non-governmental organisations. The agenda for the workshop is presented in Annex 1, and a list of participants is available in Annex 2. Copies of the presentations and this report are available on the Smart Villages website (www.e4sv.org).



Sir Mike Gregory, University of Cambridge

Session 1

The Smart Villages concept

John Holmes, Smart Villages Initiative

John Holmes summarised the global energy access statistics as the motivation for the Smart Villages Initiative, and the driver for the inclusion of Goal 7 in the Sustainable Development Goals. Energy access is also a prerequisite for achieving most of the other Sustainable Development Goals. The concern of the Smart Villages Initiative is that access to modern energy services should act as a catalyst for development in villages, bringing improved health and education, stimulating local enterprise, enhancing food security, and enabling new opportunities for democratic engagement.

The concept of smart villages is intended as a rural analogue to smart cities given that 47% of the world's population and 70% of the world's poor live in rural communities. Technological advances are shifting the balance of opportunities between cities and villages.

The Smart Villages Initiative focuses on sustainable local energy solutions for rural communities. It aims to provide an insightful "view from the frontline" of the challenges of village energy provision for development and how they can be overcome. The initiative will also communicate the consequent messages to policymakers and development agencies. Engagement programmes are being run in six regions (East and West Africa, South and South East Asia, Central and South America), which bring together the key players. The project team is based at the Universities of Cambridge and Oxford; key partners are the national science academies and their networks and Practical Action.

Cross-cutting activities include a series of "forward look" workshops in which leading researchers are brought together to consider cutting-edge developments that could make a substantial difference to village energy provision and use in 5, 10, or 15 years' time. The aim of the current workshop is to review potential technology breakthroughs over the next 5 to 15 years that could create significant new opportunities for productive enterprises in rural communities in the developing world.

Distributed manufacturing in smart cities and smart villages

Sir Mike Gregory, University of Cambridge

Distributed manufacturing has a number of key characteristics, notably:

- Effective quality control at multiple and remote locations through digitalisation of product design, production control, demand and supply integration
- Quick response and just-in-time production through localisation of products, point of manufacture and material use
- Personalisation of products tailored for individual users
- New production technologies that enable product variety at multiple scales of production
- Enhanced participation and interaction of designers, producers, and users

Mike Gregory explained that distributed manufacturing offers the promise of local production in off-grid communities. It can capture value locally, producing tradable goods. We may anticipate that appropriate industrial structures and business models will be enabled by easy access to product and manufacturing knowledge. While work will be needed to tailor approaches to different contexts, the principles are scalable and are not dependent on advanced technologies (other than internet access). Orchestration of a global network of participants in a value chain is the key innovative challenge.

Distributed manufacturing is likely to focus on small- to medium-size companies which can grow quickly in a way that very small startups cannot. It enables local production units to access world markets and reflects a return to a more local, village-scale approach to manufacturing.

Consideration is being given to a joint UK-India initiative on distributed manufacturing aimed at enhancing the growth and productivity of Indian and UK manufacturing SMEs. In India, such an initiative could help achieve the national objective to grow manufacturing from 16% to 25% of the economy (providing significant new employment opportunities). It is attractive because it can enable the direct engagement of people in remote and less-developed areas. India is keen to leapfrog to the next level of sustainable manufacturing. For the United Kingdom, such an initiative offers a number of benefits including a mechanism for accelerated innovation through rapid scale up and an extension of the UK manufacturing ecosystem to include Indian businesses.

In the subsequent Q&A, Mike Gregory recognised the challenges of distribution for manufacturing in remote communities but indicated that some significant fraction of such local manufacture could be for local markets. Moreover, knowledge and expertise could be sold, not just chunks of metal. Opportunities will be dependent on the specific context. For example, garment manufacture is more amenable to a distributed manufacturing approach than large-scale chemicals production. The former is also more likely to provide significant employment opportunities than the latter. Some economies have developed by going through a phase similar to distributed manufacturing.

Import tariffs can be a problem, and an example was cited wherein complete systems could be imported at zero tariffs whereas components attracted 40% duty. Consequently, local sub-assembly was stifled. Governments therefore have to establish appropriate tariff structures.

Advances in refrigeration and their application in remote villages in developing countries

Ian Tansley, Sure Chill, United Kingdom

Sure Chill is a UK-based technology company that has developed a unique patented refrigeration technology that delivers accurate cooling temperatures and energy storage while working with nature. It addresses key challenges for off-grid communities in the developing world: over 75% of vaccines are damaged by inaccurate or unreliable cooling, and 40% of food production is lost post-harvest. The world's requirement for cooling is also increasing, particularly for air conditioning for the Asian Pacific middle-class anticipated to grow to 3.2 billion people by 2030 with an annual spending power of US$32 trillion.

Ian Tansley explained the scientific basis for the technology, in particular that water is densest at 4°C. Cooling applied at the top of a vessel consequently results in water at 4°C falling to the bottom, providing a constant refrigeration temperature. Ice build-up at the top of the vessel results in an energy store that can last for around 10 days, providing water at 4°C as it melts. The technology is therefore suitable for situations where electricity supply is intermittent. The ice store acts as a battery, which can be recharged indefinitely.

A further advantage is that temperature conditions across the refrigerator only vary by around 0.5°C, whereas the temperature variation across conventional refrigerators can be up to 5°C. Many vaccines are in fact rendered ineffective by being made too cold in such refrigerators.

Ian Tansley, Sure Chill, United Kingdom

Application of the technology for medical refrigerators has been supported by the World Health Organisation and by the Bill and Melinda Gates Foundation: 12 models are deployed in over 30 countries. They are manufactured in the United Kingdom, South Africa, and India. A passive version of the device, only using ice as the effective energy input, has been demonstrated in tests to be capable of delivering refrigeration for 40 days from one ice load.

Preserving agricultural produce with this technology can reduce wastage, improve quality, and provide flexibility in the timing of sales, thereby increasing the sales price. It also supports the production of high-value crops for sale to markets. Whereas refrigeration for vaccines is a relatively niche market, cooling for agricultural produce and for domestic applications is a major international market.

In the subsequent Q&A, Ian Tansley explained that the refrigerator is a relatively simple system and can be made in developing countries. In order for companies to invest in scaling up the manufacture of the refrigerators, it is appropriate that the technology is not made open source: if everyone can make them, companies will not invest. Manufacturing in South Africa and India is under licence through which Sure Chill is paid a royalty. This is their business model: they are a technology company not a manufacturing company.

The refrigerator manufactured in India takes 12 to 15 hours to get to a full charge, which then provides 12 days of cooling. The charging time can be reduced if a larger compressor is installed. An alternative system based on a 500 W solar array takes two days to get down to the required temperature and then provides seven days of cooling.

A product for the agricultural market has not yet been developed so costs are not available. The technology is easily serviced and should offer a 10 to 15 year lifetime with minimal maintenance. However, there is pressure to reduce the base price of the refrigerator, which could reduce the reliability and lifetime, factors that are not fully valued.

Surechill see the biggest potential market as the off-grid sector in India which it aims to reach through licensing the technology to big domestic fridge manufacturers with good distribution networks. The key is to make the product affordable for domestic users. Currently refrigerators sell at US$40-50: the aim is to reduce this through mass manufacturing.

Low-cost thermally-powered pumps

Tom Smith, Thermofluidics Ltd

Tom Smith explained that Thermofluidics Ltd. was spun out from the University of Oxford Engineering Department in 2006. They have developed a technology that can convert low-grade heat to mechanical work and electrical power. The technology uses cheap materials and simple processes and can be supported by the local supply chain. Various energy sources can be used such as crop waste, biomass, and solar. It can be readily serviced in the field using spare parts stocked locally and has low theft appeal as there are no high-value components.

A challenge for water pumping technologies is to increase the power density. Whereas one approach is to increase the frequency, Thermofluidics Ltd. increases the pressure amplitude. A thermal solar-powered water pump has been trialled in field tests supported by the Welcome Trust in India, Kenya, and Bangladesh. It supplies enough water to irrigate 0.5 Ha (1 l/s) at low head, or 0.2 Ha at 10m lift. It is robust and field-maintainable and has no moving parts. The target retail cost is US$250-300.

Current technologies to undertake irrigation include human power, which requires substantial human energy input, and can support a maximum of 7m lift); petrol and diesel engines which have low capital cost (around US$100) but high operating costs for fuel, spares, maintenance, and depreciation; and photovoltaic-(PV) powered pumps (centrifugal and positive displacement), which have high costs and high theft appeal (cheaper versions wear out in less than a year).

Thermofluidics Ltd. is also developing a hydro-acoustic deep well pump that has an efficiency exceeding 75%, has been beta testing to 30 m in University of Oxford, and has the potential to lift hundreds of metres. Similar thermofluid–photoelectric approaches are being used for low-grade heating and cooling applications. They have the potential to provide cheap, reliable refrigeration and heat pumping, amplifying the capability of a limited electricity supply.

In Q&A, Tom Smith indicated that their intention is that local manufacturers should make the pumps. The Thermofluidics team are working with local NGOs who operate as social businesses to help local manufacturers to set up. Import duties and tariffs on components are a key issue. Solar collectors are typically over-engineered for these applications as they are bought off the shelf: there is consequently an opportunity for cost reduction.

It was suggested that "proving factories" as used in the automotive industry could help speed up scale up. Such proving factories typically employ 15 to 20 people: they take ideas and test out how they might be scaled, examining issues like sourcing components, required accuracy, and design for market, etc.

Session 2

Service value test

Malcolm McCulloch & Anna Clements, University of Oxford

Malcolm McCulloch and Anna Clements spoke about their work involving case studies of rural electrification in Kenya and Bangladesh and their tests of value to local communities of electricity services. They began by stating that systems have to create value for people. It is necessary to know "what are people's aspirations and what are their capabilities". They presented case studies in Kenya and Bangladesh that they have worked on. The aim of any project is to deliver an energy system that contributes to social and economic uplift. The recent large-scale deployment of solar home systems has often not led to this.

The first case study presented was in the town of Lemolo B., in Kenya. A "service value test" was used as a gauge of the community's collective aspirations. There were three focus groups—10 women, 10 elders, and 10 young people—who were asked questions about household and community services. Using visual illustrations of the various services, participants were asked to identify their values and then attempt to quantify them and then verify. People were asked individually then shared their values with the group. The results were displayed in a way that is useful for deployment: via a service value map. The near-term economic benefit of an intervention was plotted against the ease of delivery as a first intervention for these service value maps.

In households, lighting and mobile phone charging are priorities. TV is also a high priority as are income-generating services such as incubators for chicken eggs, fridges, shavers, and grinders. At the community level, a health centre, water, education, and improved roads were priorities. Income generation

Anna Clements, University of Oxford

through agro-processing grinders, welding, and others were also identified to a certain extent.

Research was carried out on the "current energy culture" of the village via 30+ questionnaires aimed at understanding the existing economic and material culture. These questionnaires were also verified by observations and interviews with key stakeholders such as government officials. Kerosene lighting is a large expenditure, as well as wood for cooking and fuel for motor-bikes. Analysed further, kerosene expenditure in the community ranged from 50 to nearly 400 Kenyan shillings per week ($US0.50–4.00/week). This expenditure was plotted against cumulative people counts enabling the total income for the community and an approximation of an optimal flat rate energy service charge to be calculated. The trade-off of affordability versus the service provider's financial viability in the form of the optimal flat rate energy service charge came out at 150 Kenyan shillings (US$1.50) per week.

This dataset was able to provide a useful background for a 3 kW PV project that was implemented to help (initially) 50 houses in the Lemolo B community. Homes in this community do not require much power; therefore, the system that was employed used batteries that are charged at a central battery hub, as this was more cost effective than extending the mini-grid to people's homes with copper wire. Additional income-generating services were also focused at the generating and charging hub, such as a grinding machine and an egg incubator.

Monitoring will allow the system to be optimised. In terms of the ownership model, the community will take ownership as a cooperative after approximately five years.

Malcolm McCulloch and Anna Clements spoke of other places where their service value test had been applied: in a community called Echareria in Kenya and also in a Bangladeshi community. The communities and households interviewed showed a diversity of values placed on different services.

In the Q&A, one participant remarked that the 150 Kenyan shillings/week price was the same price used by Azuri in their commercial pay-as-you-go solar systems. In terms of community aspirations and capabilities, a participant asked, "Why ask people what they want rather than what is a good life?" Phrasing the question is crucial about what people want, need, and would like to see. Energy literacy was low in the communities sampled, so it was assumed people answered what they wanted without a bias towards energy systems. It was recognised that energy access is only one part of infrastructure, but it could potentially catalyse the introduction of other services such as roads or hospitals.

Low-powered direct current (DC) motors for fans and pumps

Paul Lefley, University of Leicester

Electric motors are usually either induction motors or brushed motors, with a third type – brushless motors – becoming available more recently. In the 1880s, Galileo Ferraris and Nicola Tesla developed induction motors. These require alternating current (AC) to run. Speed variation in these motors is either difficult and costly, or simple and grossly inefficient. They are used for low-speed applications only. Low-power single-phase induction motors are generally used for bathroom and laptop fans.

For low to medium power (100 watts to 1 kW) applications, one needs an external capacitor to start the induction motor. These are used for larger air handling units and have better efficiency. The efficiency is better (60-80% efficient) and they are more robust than brushed motors being brushless so there is little to wear out except the bearings.

Brushed motors[1] can be powered by low-voltage DC and are used in power tools, for example. High-voltage AC brushed motors are used for sewing machines, high-power hand driers, etc.

Variable speed is easy to achieve and efficiency is 65-85%. However, construction (particularly of the armature) is not simple, and they are prone to wear. There are many components that can wear out, and failures of the armatures and windings on DC brushed motors are common.

As well as induction motors (for AC power) and brushed DC motors, there are brushless DC motors. These motors rely on an inverter to modulate the currents in the "stator", rather than using a commutator. Brushless DC motors behave essentially the same as a brushed motor without the brushes. They are a relatively new electric motor technology appropriate for non-rigid standalone power sources, and can be relatively simple. They have no windings on the rotor and use only magnets. Variable speed and high-speed operation are achievable, but they require a power inverter to run. Efficiency is 80-90%. Speed can be fixed or controlled even when supply voltage varies. They are not low cost due to the electronics (i.e., inverter technology). Brushless DC motors are the focus of active research. An aim is to reduce the complexity of the windings on the stator and to run the motor as a single-phase rotor so it then needs to have a rotational bias. Mass manufacturing in developing countries is possible.

Developments needed to make brushless DC motors more appropriate for a standalone power source in a remote village are:

1 Footnote: brushed motors are so-called because the original designs needed copper brushes to contact the commutator - a split-ring device used to reverse the current at the point which the torque on the DC motor would change direction when the rotor coil moves through the plane perpendicular to the magnetic field supplied by the stator (stationary part of the motor).

1. Bring down the cost by:

- Reducing the number of motor winding phases from three to one (this is only acceptable for fan applications, but not where high starting torques are required).
- Reducing the cost of the electronics, if the motor is single phase winding (reduced electronic components count by about 20%).
- Mass manufacturing: most steel and copper components could be made in developing countries. Only the magnets and electronics need be manufactured in developed countries.

2. Simplify the motor where possible:

- Embed the electronics within the motor.
- Make the motor "plug and play": easy to use and install.

In the Q&A, the cost penalty for having the circuitry required for brushless DC motors was discussed. There is also a need to establish component ratings to avoid failure. Participants questioned whether a largescale shift to brushless DC motors would result in any materials shortages. Paul Lefley replied that there should be no such problems

In response to a question relating to hydro generation, Paul Lefley noted that brushless DC motors are, in effect, alternators and could therefore be used as generators (much like a standard hydro turbine). They can consequently be used reversibly: to pump water to a head and also to generate electricity through flow. Brushless DC motors are ready for production.

Off-grid compatible appliances for social and industrial enterprises in developing countries

Grant Kopec, University of Cambridge

Grant Kopec gave an overview of his recent work for the Smart Villages Initiative looking at the future of DC appliances and how they may fit into off-grid contexts. DC systems in a typical house in the United States would reduce energy use by around one-third compared to a similar AC system. DC solar home systems have lower capital costs as there is no need for grid synchronisation, and there is potentially less overall copper use.

The main market for DC appliances has historically been in transport. DC appliances are generally more robust to vibration and contamination and easier to repair than comparable AC appliances. Grant Kopec hypothesised that DC micro-grids are, on balance, at least as cost effective as AC micro-grids. In most cases, they are more energy efficient. Therefore, the barriers to adoption of DC micro-grids and appliances are in the areas of standards, education, awareness, and economics.

There are now around 200 DC appliances on the market. Fundamental components are items such as motors, lighting, circuits, heating elements, and battery energy storage. Almost all of these are native DC, which means they can operate on DC current without the need for an additional inverter.

There are big efficiency savings from going from AC to DC. For lighting, DC is 73% more efficient and heating is 50% more efficient. It can also have significant efficiency improvements for cooling (5-50%), motors (5-15%), and cooking (12%). For a typical US household, the efficiency is improved by approximately 30%. AC/DC conversion can have efficiency losses, however.

Grant Kopec looked at the research done on direct comparisons of AC and DC micro-grids. They are comparable in respect of safety and component production. Capital cost depends on the specifics of the micro-grid system; some DC systems cost more than AC systems and some less. Energy efficiency and operating costs are improved for DC systems. DC micro-grids are also easier to install, and power quality is improved.

Grant Kopec, University of Cambridge

A crucial aspect for the future of the DC market is the learning rate—the decrease in per-unit prices as production increases. For lighting, circuitry, electronics, and batteries, this learning rate is determined by advances in technologies (along with economies of scale), and their learning rates are more simply predicted. However, for DC motors and heating elements, Grant Kopec stated that their learning rates were governed by factors other than just technology advances and economies of scale.

Summarising various DC appliance surveys, Grant Kopec noted that DC appliance availability lags AC appliance availability, and costs are generally higher. Whilst the overall system cost (capital + operating) of an off-grid DC power and appliance system may be lower over time, short-term incentives bias the purchase of cheaper AC appliances. There are market inefficiencies—supplies and choice aren't always available, and consumers are uneducated in the intricacies of choosing DC versus AC appliances. There is a lack of reliable studies on the impact that the introduction of DC appliances have on productivity.

Going forward, there are a number of key barriers, questions and wildcards hindering DC appliance uptake:

- Higher appliance prices plus upfront infrastructure costs: how quickly will DC appliances achieve economies of scale so that they are generally available at low cost?

- Integration with existing infrastructure: many homes may already have AC wiring, but there are several intriguing options for dual AC and DC systems using the same wiring.

- Voltage standards and related plug standards increase confusion. The DC sector is effectively still a cottage industry. DC grids are not inherently less safe than AC grids, but standards are less well known. According to the IEEE: "The lack of practical experience and safety issues regarding the utilization of DC powered buildings still works against DC adoption." How will these standards evolve as DC appliances with high power draws (>1kW) become ubiquitous?

- Energy demand: the adoption of some technologies might stress the current or even future designs of household DC (or AC) electrical systems. Does one have to go to higher voltage and replace the entire system? Examples of high future loads are: electric vehicles (3-10 kW), heating and cooling (1 kW and up for heat pumps), cooking and other water heating activities (1.5 kW per hob burner) and shop tools and processing equipment (1 kW and up)

- Support is needed for financing and maintenance.

In the Q&A, the cost of DC systems and the safety issues at high voltages were stressed as key challenges. Is there another way forward with something in between AC and DC such as a quasi-square wave? Also, what is the solution to energy storage? Putting power into a battery and taking it out again loses around 30%, which reduces the overall efficiency of the system. It is difficult to find mass manufactured components for DC. Brushless AC motors could run on DC at low voltage without any need for conversion. A power drill for 230V AC could run at the same speed on 120V DC. There is no group to take responsibility for the sharing of these developing ideas.

SESSION 3

3D printing for rural villages

William Hoyle, techfortrade, London

William Hoyle spoke about his and his organisation's work on advancing 3D printers in the developing world.

He began by explaining his interest in 3D printing. 3D printing could be a disruptive innovation that contributes to poverty alleviation in developing economies. It offers the opportunity to establish a bottom-up rather than top-down contribution to addressing material poverty. 3D printing may potentially be a tool for resource constrained off-grid communities to draw on, offering a new model for consumption and innovation that is less dependent on globalised supply chains.

William Hoyle then explained how he got into 3D printing in relation to the agricultural trade. While working in Zambia he read about 3D printing and was inspired by the opportunity to send things digitally rather than physically across borders. This led to him setting up a competition, the 3D for Development Challenge: http://bit.ly/1Xh7lLu .

He has since run workshops in South Africa, India, Bucharest, and Brooklyn and believes 3D printing could be as disruptive a tool as the mobile phone in Africa. It fundamentally changes the distribution model; a user can be designer, producer, and distributer all in one. The system of 3D printing is like an eco-system.

The current foci of William Hoyles' and others' efforts in 3D printing fall into four categories: equipment, education, enabling local markets, and entrepreneurship.

Equipment

People living in the developing world often lack the necessary items to engage in 3D printing. If they have access to printers and filament, these are often expensive, imported, and difficult and slow to repair. There are systemic challenges such as high import tariffs and shipping costs. Local economies would benefit from learning to produce more components locally.

Key interventions to solve these problems would be using locally made 3D printers, low-cost hardware, and recycled e-waste parts. Filament extruder and processes for local production of filament from recycled plastic are needed.

Education

As this disruptive technology is progressing globally, emerging economies will need young people who understand and are excited by its potential. This can be achieved by an initial focus on schools as a channel for Retr3d sales, as is being done in Nairobi. Retr3d is a framework dedicated to affordable 3D printing equipment for developing economies by building 3D printers from e-waste. In Nairobi, there is a partnership with a local teaching partner and Retr3d, and a commitment to open source.

Enabling Local Markets

To ensure that local value chains benefit as 3D printing moves into emerging markets, necessary infrastructures—such as talent and equipment—need to be in place as market opportunities emerge. To start to make a case for inclusive value chains and local market development, techfortrade will run 'proof points'—marketing slang for demonstrated examples that offer irrefutable evidence of the quality, importance or uniqueness of concepts—using "Digital Blacksmith" workshops for prototyping and fabrication for client projects and needs.

Entrepreneurship

As 3D printing equipment becomes more prevalent, including in schools, and knowledge of how and why to use 3D printing increases, it is techfortrade's vision that makers (the term used to describe people who produce things with 3D printing) will become entrepreneurs, solving local, regional, and even global problems. They will develop products that turn into business opportunities that sustain and grow their work. This can be helped by design challenges and other events to spark innovation.

William Hoyle is also involved in the 3D printing enterprise, the "Ethical Filament Foundation" that works in Oaxaca, Mexico. Printing filament can be produced locally from recycling polyethelene terepthalate PET bottles. The filament sells for US$70 per kilo and the bottles earn the pickers US$0.17 per kilo. They are currently working to develop a quality standard for the filament using fair trade style standards for social, economic, and environmental considerations. Partners in the enterprise include FabLab Oaxaca, STICLab in Dar es Salaam, and ab3D. Products have included a queen bee incubator, a mushroom incubator, and casts for "jigger" flea sufferers.

3D printing can potentially make manufacturing like agriculture: scalable and empowering for rural people. Plastic collected, shredded, and shipped to China has no tax. For plastic collected and turned into a new product, tax is paid, so the market is skewed towards shipping rubbish. There are quite big agricultural companies in the world, but none can hold a candle to the likes of Volkswagen and Walmart, despite the fact that agriculture is our only vital industry. The reason for this is that manufacturing and distribution both currently benefit from economies of scale. In contrast, agriculture is scalable: anyone with a little land can grow something.

William Hoyle, techfortrade, London

In the Q&A, it was asked what the prospects are for using 3D printers to produce motors. It is only a matter of time before there is a technology to print metal, plastic, and the electronics to make that possible.

The power consumption of the printers is 140 watts if using a heated bed, and only 60 watts without. A prosthetic hand can be printed in around 10 hours.

There is no telling what people will want to print, and it won't be limited to a particular sector. Customers come up with their own ideas.

Precision farming in developing countries

Harshal Galgale, Kisanhub, Cambridge

Harshal Galgale is the founder of Kisanhub, a cloud-based business to business (B2B) software as a service (SaaS) platform for agricultural enterprises providing readily accessible relevant data.

Farmers have a lot to do in a short time and are working in a complex and globally connected ecosystem. Lots of data is captured, but it is not shared, so poor farmers cannot make use of it. By gathering data that is relevant and making it available to the farmers, they can make use of the information and start to make decisions based on that information in conjunction with information on weather and economic data. This enables agribusinesses to take more data-based decisions, to reduce yield losses and input costs, and to maximise market opportunities.

The sources for the Kisanhub database are the farmers' own data, publically available information on weather and markets, local/national statistics, precision agriculture research models, social media, and farm-based sensors.

Harshal Galgale explained Kisanhub's plans for expanding from the UK to potentially operate in India. An example showed satellite data being used to identify field vegetation quality in India.

Further analysis is possible using the datasets, for example on the incidence and causes of pests and other important agricultural factors. This all enables farmers to grow more with less by making better use of information.

In the Q&A, the wider benefits of the technology were identified as being a driver for youth to stay in farming and improve literacy and opportunities. It was pointed out that this is high-tech industrial agriculture, and there is nothing currently like this being used by smallholder farmers in Africa. Seed improvement is only part of the story. Improved distribution methods of agricultural products are also necessary.

Data for de-risking financing is a big challenge in Africa and making things like soil maps available is hugely beneficial. It was suggested that this technology may be appropriate at the local government level rather than trying to disseminate to each individual farmer in developing world contexts. Farmers provide base data such as field boundaries, but information is additionally gained from drones or satnav images. KisanHub is small and trying to build capacity while trying to understand what farmers want.

SESSION 4

Panel discussion - what are the key opportunities and challenges for the adoption of breakthrough enterprises and markets in the next decade?

Chair - John Holmes

A new concept in tidal turbines

Johnny Chan, City University of Hong Kong

Johnny Chan explained the progress he is making in his research towards a low flow tidal hydropower turbine. The current trend in large tidal devices is that they are increasing in size—up to 1MW, with devices designed for high velocity flow rates. Designing tidal energy converters with the ability to generate power in low flow rates (<2m/s) can greatly increase the tidal energy potential worldwide, and such devices could be used in rivers.

The strategy is to design a horizontal axis tidal turbine with a low RPM and high torque rotor for the low flow rates.

A 35cm turbine can generate electricity with a water flow rate as low as 0.4 m/s The generation is only 30% of the theoretical efficiency possible but still produces 4kW of power. A scaled prototype has been installed to gather real-world data.

The next stage of development is to try to use multiple small turbines together rather than one large turbine. Small turbines are cheaper to produce than one large one, and sixteen can be put together to increase the generation capacity. Work is ongoing to use modelling to modify the duct shape, and to work on anti-fouling methods to reduce maintenance of the turbine. Work is also being done on developing bi-directional capacity to capture energy production on both the ebb and flood tides.

This is a technology that needs to be explored more. People have always focused on big tides—this approach to small tides could be good for remote island communities.

Johnny Chan, City University of Hong Kong

In the Q&A, cost was mentioned. As the first installation was only in August the project is still in early stages. One turbine in China may cost US$200 but mass manufacturing may reduce it to US$20. Marine growth can be solved with paints. Bearings may get salt damage and corrosion and need replacing. A big problem is rubbish on the coast blocking the turbine. Computational fluid dynamics modelling is needed to check whether there are issues associated with scaling down the arrays.

Identifying user-perceived value as a tool to long-term success of initiatives targeting lower-income communities

Stephanie Hirmer, University of Cambridge

Stephanie Hirmer identified three major challenges that hinder the sustainable uptake of initiatives targeting low-income customers: appropriate design, after- sales services, and appropriate marketing. There have been major improvements in the fields of appropriate design and after-sales services, but only limited progress in appropriate marketing.

While appropriate design still poses a continuing and significant challenge, there have been major advances in adopting designs to low-income households. To name two successful examples: the Anagi II cookstove, made locally from local materials, was modified over a period of time to be most effective for a particular Indian community that required two compartments for their traditional food, one for fast and one for slow cooking. This has greatly increased product uptake in that particular geographical area. A second example of appropriate design is solar lanterns, many of which now allow mobile phone charging, as developers and designers have acknowledged that this is of great value to low-income customers.

However, in both of the above examples, several product modifications were necessary before the product was appropriate for the target market.

In a similar way to the above examples of appropriate design, major improvements have been made in after-sales services. Many social enterprises are now including product warranties as well as access to spare parts and a local after-sales point of contact.

Appropriate marketing, however, has mainly focused on identifying the right communication channels such as radio, TV commercials, and road shows, but the actual message that is meant to trigger an understanding of how the product aligns with the actual customers' needs has been neglected. One reason for this is that marketing is usually something that is not part of the culture of NGOs or development agencies and is mostly associated with profit-making, and hence is seen to have a negative connotation. Therefore, marketing to low-income customers represents an unexplored avenue in achieving acceptance of development initiatives.

An appropriate initiative for lower-income customers is not a good initiative if it is not perceived to be of personal value. When bringing electricity to rural communities for the provision of better lighting, householders often do not perceive this to be of personal value because the benefits of such initiatives are not well communicated to them. Despite capacity-building initiatives, awareness-raising campaigns, and after-sales service, shortly after projects have been handed over (from the developers to the locals), problems have frequently started to show. Stephanie Hirmer has observed a clear lack of interest in simple maintenance tasks and consequently equipment soon stopped working. This indicated that the end-users of these particular electrification initiatives did not value electricity in the way it was being explained and could not relate to it otherwise.

Therefore, to understand what is important to lower-income markets, one has to spend time listening to people's priorities instead of trying to convince them that what has been developed to meet their needs is something they should want based on our assumptions. However, it is important to note that people themselves are often not aware of what they truly value; therefore, techniques need to be used that allow people's priorities to be deduced by extracting them from indirect links. This can be done by applying conventional marketing techniques to a developing country context.

In many developing countries there is a high illiteracy rate—providing probes with pictures is an appropriate technique. Equally, one has to be aware of external biases that can change people's short-term perception of what is important. For example, arriving at a village to do market research in a big four-by-four with 'Water Aid' written on its side will unavoidably skew people's value perception of their need for water. Understanding why something is important to the end-user will lead to an improved understanding of how a development initiative can be beneficial.

Stephanie Hirmer has developed a "user-value wheel" as part of her PhD research that allows identification of what is perceived as important to low-income customers by matching conversations to an applicable value category. She used the example of Scola, a widow from the village of Biwindi in Uganda, to demonstrate the methodology behind the user-value-wheel. Scola chose to prioritise a flush toilet over a pit-latrine. Using the "wheel method", Stephanie identified that this decision was made in the context of a number of applicable value categories: aspiration, security, and safety.

Using this user-value wheel, one can identify and map what is perceived to have the most personal value to potential customers and hence create a product or service whose values are aligned with the benefits that the customers desires. This in turn leads to the sustainable uptake of development initiatives.

Youth Entrepreneurs and the Cambridge Development Initiative

Georgia Ware, University of Cambridge

Georgia Ware is a fourth-year manufacturing student who described the activities and formation of the Cambridge Development Initiative (CDI). The CDI is a student organisation that employs its own model of development.

It is focused on innovation and entrepreneurship—students can take risks that others cannot take. A student-led approach can be powerful. CDI runs projects based on education, engineering, entrepreneurship, and health.

Georgia Ware went with the CDI to help run their eight-week entrepreneurship training course in Dar Es Salaam, DAREnterprisers. They piloted the course for the first time at the University of Dar Es Salaam in July and August 2014 for 21 students. The Cambridge students act as facilitators and technical consultants for the courses, which are focused on human-centred design.

In 2015, CDI collaborated with the Smart Villages Initiative to run a competition on energy access for students and recent graduates that attracted nearly 100 entrants. Finalists undertook the entrepreneurship course, along with students recruited through other tracks, on its second running in July/August 2015. A large social entrepreneurship conference was held at the end of the course which attracted over 800 participants. At this conference, supported in part by the Smart Villages Initiative, the winner of the off-grid energy challenge was selected and awarded a prize of US$3000.

Georgia Ware detailed some examples of the finalists' projects and subsequent spinout companies. These included Chemolex—a solar and battery based rural lighting system, Citigas—a Rwandan biogas provider and consultancy, and Dream Line Energy—another off-grid solar energy provider. The success of these and other initiatives like them shows the scalable impact of a small group of entrepreneurs.

Georgia Ware also spoke of the significant and valuable learnings to the members of the Cambridge student teams. Her vision for the endgame of the CDI is to turn the initiative into a positive exchange, where students travel from Tanzania to Cambridge to work on problems in the UK and vice versa.

Continuity in the organisation can help to retain valuable knowledge gained and lessons learned to avoid repeating mistakes common to some student development organisations.

Frugal Innovation: How to do More (and Better) with Less

Jaideep Prabu, University of Cambridge

Jaideep Prabhu summarised his thoughts on the concept of "frugal innovation". Throughout his career he has studied innovation. In 2007/8 he started visiting places in India, and noticed their approach to innovation was different. It was frugal, flexible (with lots of lateral thinking), and inclusive—designed to bring people from outside of the formal economy to within it.

As an example to illustrate his point, in an affluent society, a high-end refrigerator can cost US$3000. You can talk to it, and the focus is on the technology. In contrast, in India a clay refrigerator has been developed that costs around US$30 and which can keep fruit and vegetables fresh for five days. Mansukh Bhai, who comes from a village in Gujarat and has only a high school education, designed the refrigerator. He then upscaled his enterprise by training local women to make them.

Another striking example of frugal innovation is the US$20 blanket that has been developed for maintaining a baby's temperature that can substitute for a US$20,000 for a baby incubator. Frugal innovation occurs when a lack of resources provides the stimulus for innovation of products and services. A good example of this is the Stanford course on "Design for extreme affordability", which has produced technologies at one hundredth of the cost of normal products.

Why does India need frugal innovation? 40% of Indians live outside the formal economy. The lower segments of this informal economy are very large and relatively untapped. They are off the electricity grid and have limited access to healthcare and education. At the same time, there is a changing class structure, and India can be seen as a microcosm for different parts of the world. The "base of the pyramid" market is growing rapidly and is now worth US$10 trillion.

Harish Hande and his company SELCO are another example. He used a service model to scale up his venture. SELCO aims to provide a complete package of product, service, and consumer financing to provide clean energy for everyone.

Harish Hande learned his best lesson from a fruit vendor, who said that for lighting, "300 Rupees a month is too much, but 10 a day is fine." Consequently, SELCO charges lights during the day and rents them out to vendors at night, and made it so that the cost of a solar lamp replaces the cost of kerosene. Other examples are found in the Greenlight planet solar lighting kit, only costing 800 rupees (US$10), or Simpa Network that offers prepaid, pay as you go, and instalment plan elements for solar home systems. The Azuri model starts people at a basic level, and then they progress up the "energy escalator".

The world needs frugal, flexible, and inclusive innovation. The United Kingdom and the West can gain by engaging with their counterparts in emerging countries. The small and the large, the new and the old can work together to improve lives everywhere.

In the Q&A, Jaideep Prabhu was asked for an example where frugal innovation has gone on to success in the developed world. He provided the example of GE developing a small, affordable, and robust ECG machine for rural communities, that is now successful across the developed world. IBM has set up a centre for frugal innovation in Nairobi.

A further question concerned how businesses can be scaled up once created. Training and replication are possible approaches. Another way is to partner with big organisations—governments and major business. A key problem is the last mile, which is well-recognised. An example addressing this is mobile telephony for banking, where there will be big global growth in the next twenty years.

Discussion of key messages to take away

Chaired by John Holmes

The discussion began with a reflection that it is difficult to understand why people do not do the crucial things for the last mile. There is a need to understand people's behaviours and motivations much better. Some general questions should always be asked for any intervention: what is the value proposition that we are putting forward?; what is the end game and what are the steps so that we don't lock ourselves in?; how do we get up the escalator to the full system?

Development projects need to make use of the intelligence of people who live in the communities they are trying to help. The human element is really important and local talent can be crucial. For key technical positions and for projects, it is important to select human resources carefully, maybe from outside the village, and to consider how to pay them. If they do not perform, then you should replace them.

Interventions are part of bigger economic ecosystems and one needs to look to investors. It is also important to think of any longer-term impacts that interventions will have.

Another factor to consider is that, in many instances, poor people are (often out of necessity) short-sighted in terms of finances, and this limits what they can do. People outside the system can support them through appropriate mechanisms such as secure money lending which then helps them to solve their own problem. The bottom billion and the last mile need to be tackled by policymakers because it must be on the political agenda.

Concluding comments

Bernie Jones from the Smart Villages Initiative gave some closing remarks and outlined the next steps in the project. He noted that it was good to find so many fascinating and productive areas in which radical new ideas are being generated. This is the value of bringing people together. The workshop had identified several new ideas and issues that would be reviewed and potentially addressed in future workshops.

ANNEX 1: WORKSHOP PROGRAMME

Friday 18 December 2015

9:00 **The Smart Villages concept**

John Holmes, Smart Villages Initiative Co-Leader, University of Oxford

9:30 **Distributed manufacturing in smart cities and smart villages**

Mike Gregory, Institute of Manufacturing, Cambridge

9:45 **Advances in refrigeration and their application in remote villages in developing countries**

Ian Tansley, Surechill, UK

10:15 **Low cost thermally-powered pumps**

Tom Smith, Thermofluidics Ltd., Oxford

10:45 **Break**

11:15 **Service Value Test**

Malcolm McCulloch and Anna Clements, University of Oxford

11:45 **Low-powered direct current (DC) motors for fans and pumps**

Paul Lefley, Leicester University

12:15 **Off-grid compatible appliances for social and industrial enterprises in developing countries**

Grant Kopec, University of Cambridge

12:30 **Lunch**

2:00 **3D printing for rural villages**

William Hoyle, techfortrade, London

2:30 **Precision farming in developing countries**

Harshal Galgale, Kisanhub

3:00 Break

3:30 **Panel discussion - what are the key opportunities and challenges for the adoption of breakthrough enterprises and markets in the next decade?**

Chair - John Holmes

A new concept in tidal turbines (Johnny Chan, City University of Hong Kong)

Identifying user-perceived value as a tool to long-term success of initiatives targeting lower-income communities, (Stephanie Hirmer, Cairo)

Youth entrepreneurs and the Cambridge Development Initiative (Georgia Ware, Cambridge)

Frugal innovation: How to do more (and better) with less (Jaideep Prabhu, Cambridge)

4:30 **Key messages discussion and closing statement.**

5:00 **Close**

Annex 2: Workshop participants

Name	Organisation
Ms Lara Allen	Center for Global Equality
Dr Claudia Canales	University of Oxford
Prof Johnny Chan	City University of Hong Kong
Ms Anna Clements	University of Oxford
Dr Heather Cruickshank	Independent
Dr Jonathan Cullen	University of Cambridge
Dr Shailaja Fennell	University of Cambridge
Dr Harshal Galgale	Kisanhub
Prof Sir Mike Gregory	University of Cambridge
Mr Richard Hayhurst	Smart Villages
Prof Sir Brian Heap	University of Cambridge
Ms Stephanie Hirmer	University of Cambridge
Dr John Holmes	University of Oxford
Mr William Hoyle	techfortrade
Dr Bernie Jones	Smart Villages
Dr Grant Kopec	University of Cambridge
Dr Paul Lefley	University of Leicester
Prof Malcolm McCulloch	University of Oxford
Ms Dilek Ozgit	University of Cambridge
Dr Nalin Patel	University of Cambridge
Mr Ed Phillips	Practical Action
Prof Jaideep Prabhu	University of Cambridge
Dr Mike Price	University of Cambridge
Dr Kristin Shine	Smart Villages
Dr Tom Smith	Thermofluidics Ltd.
Dr Ian Tansley	Surechill
Mr Meredith Thomas	Smart Villages
Ms Georgia Ware	Cambridge Development Initiative

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SMART VILLAGES

New thinking for off-grid communities worldwide

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