*Proc. ISES Solar World Congress, October 11 – 14 2009, Sandton Convention Center, Johannesburg, South Africa*

# Self-Assembled Solar Lighting Systems

**T.J. Cumberbatch[1], D. Berger[1], M. Gazes[1], P. Momori[2], N. Ayikutu[2], C. Mtiamoah[3], F. Akorli[4], D. Anipa[5] and F. Akuffo[5]**

[1]Center for Sustainable Engineering, Art and Architecture – Materials, Manufacturing and Minimalism,
The Cooper Union for the Advancement of Science and Art
New York, NY, USA; email: toby@cooper.edu

[2]Department of Mechanical Engineering, Wa Polytechnic
Wa, Ghana

[3]Department of Civil Engineering, Wa Polytechnic
Wa, Ghana

[4]Faculty of Applied Science, National University of Rwanda
Butare, Rwanda

[5]The Energy Center, Kwame Nkrumah University of Science and Technology
Kumasi, Ghana

## Abstract

A major problem facing sub-Saharan Africa is the absence of efficient and affordable lighting for off-grid rural communities. The kerosene-based hurricane lantern, which has served these communities for many decades, is now identified as one of the causes of respiratory health problems. Although there does exist a variety of imported solar powered lighting systems, these products are not widely available, are generally priced beyond the means of the end-user and have serious reliability issues. To address these deficits, student led teams, from the United States, Ghana and Rwanda, working with rural communities in Northern Ghana and Southern Province, Rwanda, have designed and implemented a lighting system, amenable to assembly, installation, maintenance and repair by the rural poor – that is also robust, technically sustainable and affordable. The outcome – a self-assembled, solar powered lighting system that satisfies the lighting requirements for reading, writing and household chores, and is also financially self-sustaining through local entrepreneurship.

## 1. INTRODUCTION

There is a desperate need for an economic lighting system that can be assembled, installed and maintained by the 800 million plus rural poor who live in the remote areas of the Developing World. Matching this is an immense interest in providing light for rural communities: the potential demand – and, consequently, the potential global market – is almost limitless. To be successful, the lighting system must be designed and developed with reference to its place of use, be sought after, affordable, locally implemented, and be financially, technologically and operationally self-sustaining. Currently, many rural families rely upon simple oil lamps with cotton wicks, or the more modern kerosene lanterns. These traditional light sources are expensive to run due to the cost and limited availability of fuel and replacement wicks. They provide poor quality illumination, consume fossil fuel, generate carbon dioxide, and create health hazards not only from fire risks but also the degradation of indoor air quality in the enclosed spaces within which they are used.

A major contributing factor to rural depopulation in countries close to the equator is the restriction of activities after nightfall. Truly sustainable sources of artificial light can "extend the day" – ultimately acting as an agent to reduce urban sprawl, foster education and advancement of the rural communities. Equally, the widespread introduction of such light sources may inevitably cause seismic changes in the social structures of the individual communities and the region as a whole. Whilst it is not possible to predict social outcomes, we have to believe that the economic and health impacts of this change will be to the net benefit of the individuals and

communities: indeed, as we have observed directly through our existing installations in Ghana and Rwanda, solar powered lighting systems are coveted and greatly enhance community-wide activities after sunset.
To date, we have designed, constructed, installed and tested a solar lighting system, *SociaLite*, that is amenable to fabrication in rural regions; that does not require specialized tools or highly skilled labor. Designed to utilize locally available components where possible, the system is robust, easy to maintain and repair. Our financial model, still in the early stages of development, anticipates the establishment of "social businesses" as described by Mohammed Yunus (Yunus & Weber, 2007) and Paul Polak (Polak, 2008). We envisage that these ventures have the potential to play a major role in capacity building – through the development of an infrastructure run by local entrepreneurs comprising small businesses that assemble, install and repair these lighting systems; and, through the training of local communities to maintain and operate these systems. Contingent to the success of these ventures is the establishment of a robust, self-sustaining microfinance strategy to provide assistance with the initial purchase of the lanterns by the end-user and the charging station by the community or an individual entrepreneur.

The ultimate goal is to provide interested parties with a *lighting system in a suitcase* – that is everything required to establish a complete solar lighting enterprise *under a tree*. In brief, this encompasses all the necessary documentation, tools, test procedures and sources of components to open up shop. As crazy as it may sound to bypass all the standard procedures and routes normally adopted for the introduction of a new technology to the developing world, we believe that this approach has the necessary ingredients to succeed. By importing the "raw materials" directly to their place of intended use, the local communities have a much greater appreciation of the fabrication procedure and the system technology. Instead of being presented with a sealed lantern with a molded plastic housing through the auspices of a donor, they understand that the *device* comprises components they can assemble and replace if necessary. With assistance, they are asked to supply their own lantern housing from materials that are available to hand – enhancing their sense of ownership and intellectual property.

We believe that this approach is fundamentally different from those of the many organizations throughout the Developed World whose goal is to *"light up the world"*. Characteristics common to many of these ventures are: the development and manufacture of the lighting systems are undertaken far away from the place of use; local infrastructures for the maintenance and repair of these systems do not exist; the systems are often sold at less than cost price – the subsidy being derived from a variety of unsustainable sources; the cost of the system frequently places it outside the reach of those for whom it is intended – the rural poor.

This project is ultimately about material resources, energy, engineering education, real sustainable engineering, minimalist design, the principles of energy conversion, the critical relationship between the engineer and the end-user, good design, poverty and the developed world, and entrepreneurship.

## 2. DESIGN CONSIDERATIONS

Engineering for the poor often comprises the adaptation of well-established solutions from the Developed World to satisfy a perceived demand in the Developing World. This approach takes into account neither the real needs of the intended user nor the environment within which the solution is to be implemented. These errors are compounded by the distribution of these solutions in the form of "aid" into which the issues of sustainability are not incorporated – and that are usually devoid of the principles of socially, economically and environmentally responsible entrepreneurship. The net result, so perfectly described by Ian Smillie is that ".. too many failures in the 'development business' have been ignored or covered up, condemning poor people to suffer the re-invention of too many wheels that never worked in the first place." (Smillie, 2000). In "The White Man's Burden", Easterly argues that the Developed World can help Africa emerge from poverty by providing the poor with the means to establish their own self-reliance and, through this, gain their own self-determination (Easterly, 2006). To do so reliably mandates engineers to work *with* the poor to develop sustainable, geographically and culturally appropriate engineering solutions to address their real needs.

The design of a lighting system for those at the *"base of the pyramid"* provides a broad conduit through which to introduce many important concepts to engineering students. The challenge to a first year *"Engineering Design and Problem Solving"* class in fall 2006 at The Cooper Union was to design a rechargeable lantern for use by the poorest people on the planet. The specifications called for the properties expected of such a product: it had to be physically robust, durable, easily repairable and offer the potential for local manufacture and distribution. Further constrained by the requirement to embrace the core principles of holistic sustainable design into the solution, the task presented a major challenge to the team of multidisciplinary students. By additionally incorporating the elements of entrepreneurship and business into the design specifications, the students gain insight into the constructs of real sustainable engineering and the outcome of minimalist design. Success is a mutually beneficial, meaningful dialog between students from universities in the richest country in the world, students in Africa and individuals from the poorest communities in the world.

Through attempting to satisfy simultaneously these design criteria, the students also gain an appreciation of the conflicting demands present in cross-sector programs, and the essential interplay and interdependencies of the multidisciplinary inputs into the design, launch, marketing and sustainable demand that are required for the successful introduction of a new product. They begin to understand the role of entrepreneurship, stripped of ornament and excess baggage, in new business ventures. Working in emerging markets, students see the critical function of micro-financing, the benefits gained by sharing the cost of expensive resources, the critical input acquired by including the end-user in the design process, and the need to understand and characterize the environment within which the product will be used.

In *Rural Development: Putting the Last First*, Robert Chambers writes: *"The search is for approaches which are open to the unexpected, and able to see into, and out from, the predicament of the rural poor themselves."* (Chambers, 1983) For these very reasons, this project *has its roots* and *is set* in remote, rural, off-grid locations where the design, fabrication and implementation of a solar powered lighting system are <u>approached from the perspectives of rural communities</u> in Northern Ghana and Southern Province, Rwanda. From this vista, the project teaches engineering students the need for, and the practicality of, an awareness of the limited nature of resources for every project they undertake throughout their careers. They learn that minimalist, sustainable solutions are the most responsible approach to the design of everything from household consumables, to transportation, to housing, to factories and office complexes. They begin to understand that the price that will have to be paid for the profligate use of resources today will not come due in some indefinite future and faraway place, but within their lifetimes in their own communities, and that their health and surely that of their children will depend on the choices they make now. These students discover that engineers must respond to the needs of their constituents, that they must test designs with careful evaluation procedures and learn how to frame questions that elicit the information they seek from the end user.

## 3. SYSTEM DESIGN

### Overview

From an engineering perspective, a lighting system powered by photovoltaic panels can be modeled by a *black box* into which light enters and from which light emerges. The optical energy input is converted to electrical and chemical energy a number of times before emerging as optical energy from a light emitting diode (LED). To optimize the efficiency of the system it is important that each energy conversion process operates with maximum efficiency. Some of these processes are under the control of the engineer, others are governed by the laws of nature.

From the outset, it was decided to implement the lantern recharging station as a shared resource as shown in Figure 1. The advantages of this approach over that of a dedicated panel for each lantern are that the cost of photovoltaic power is about 5USD/Wp compared to 15USD/Wp or more; that charging circuitry does not need to be incorporated into each lantern; and finally that a high capacity car battery stores sufficient energy to accommodate overcast days. The disadvantage, as we have discovered, is that some of the members within a widely dispersed community may have to walk some distance to recharge their lanterns. Increasing the number of charging stations clearly resolves the problem but at a considerable increase in the cost. Current experience suggests that we adopt a hybrid approach in which an installation contains both a central charging station and one or more smaller panels to be shared amongst clusters of distant households.

Our *standard* multiunit charging station, comprising an 80W solar panel and a 75Ah car battery, has the ability to support approximately 50 lanterns whilst accommodating up to six consecutive cloudy days. The *standard* rechargeable lantern comprises: one 4.5Ah lead-acid battery; one 60 lumen white light emitting diode; circuitry

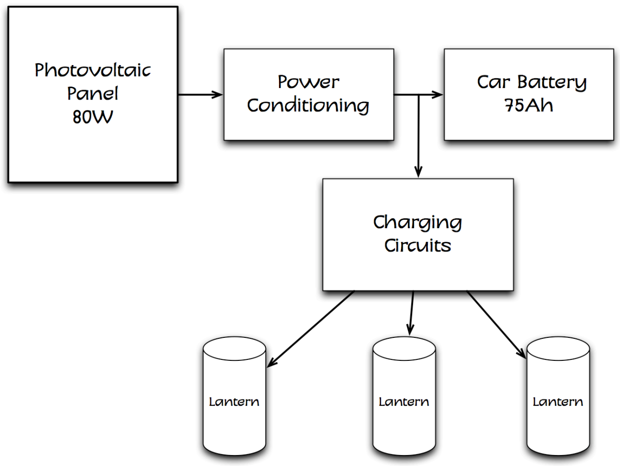


Figure 1 Lighting System Schematic

to supply the LED with current pulses of variable duration at a frequency of approximately 5kHz; and, circuitry to disconnect the battery when a predetermined level of discharge has been reached. By supplying the components in kit form for self-assembly, we believe that the **SociaLite** solar powered lighting system comprising a charging station and fifty lanterns can ultimately be installed for less 1500USD. If this were to replace its kerosene equivalent, the system could pay for itself in a year.

From an engineering design perspective, within the context of this project, every aspect of the lighting system must be analyzed in terms of both cost and efficiency as outlined in Figure 2. For example, a white LED may have a high electrical to optical conversion efficiency but the light generated is only useful if it emerges from the lantern. Adding more LEDs or increasing the drive current to compensate for poor light distribution optics may

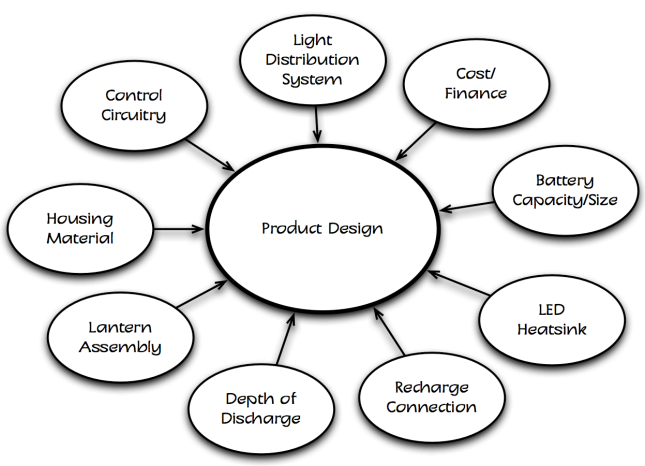


Figure 2 Design Considerations

offer a viable, though less than optimal, solution when resources are not so severely limited. In this context, the only acceptable course of enquiry is optimization of the optical system.

Lead acid batteries were chosen for both the lantern and the charging station. When compared to all other commercially available battery technologies, the lead acid battery is economic, robust and better suited to the higher temperatures generally encountered in sub-Saharan Africa. However, these batteries, in common with all others have finite lifetimes which can be severely curtailed if precautions are not taken to ensure use within a specified operating environment. Most particularly, the lifetime of these batteries is prolonged if the depth of discharge is limited to 30 – 40% of the maximum capacity, and the battery is charged using an optimal procedure. We decided that the extended lifetime gained by incorporating circuitry to accommodate these requirements warranted the extra cost.

**Charging Station**

A car battery was chosen over a deep cycle battery for two reasons: in sub-Saharan Africa, deep cycle batteries are not readily available and they are very expensive. However, the increasing shortage of metals is rapidly pushing up the price of lead acid batteries – in Ghana there has been a twofold increase in price over the last three years. For reasons unknown, accompanying the price increase has been a reduction in the readily available battery capacity from 80Ah to 65Ah.

Uni-Solar triple junction amorphous silicon photovoltaic panels (US-64) with a polymer encapsulation were originally chosen over conventional single crystal or polycrystalline silicon panels for their reduced weight (no glass) and better performance at high temperatures. Furthermore the increased physical resilience of the amorphous silicon panels virtually eliminates the possibility of damage en route to remote communities that often require extended journeys over poorly maintained dirt roads. More recently, airlines have reduced the maximum package size (Width + Height + Length) to such an extent that it is no longer possible to take a reasonably sized panel as accompanied baggage on international flights. For this reason, we have switched to a photovoltaic laminate (PVL-68) also manufactured by Uni-Solar that utilizes the same triple junction amorphous silicon technology as the US-64. This panel has the advantage that it can be rolled up, occupying very little space – and is virtually indestructible.

Circuitry to charge the lantern is built around a specialized IC designed for the optimal charging of lead acid batteries – the TI UC3906. In common with the lantern circuitry, a DIL package was chosen to facilitate assembly and repair of the printed circuit board as shown in Figure 3. Whilst surface mounted ICs would have reduced the board size, they require specialized equipment for assembly. The charging circuits are mounted

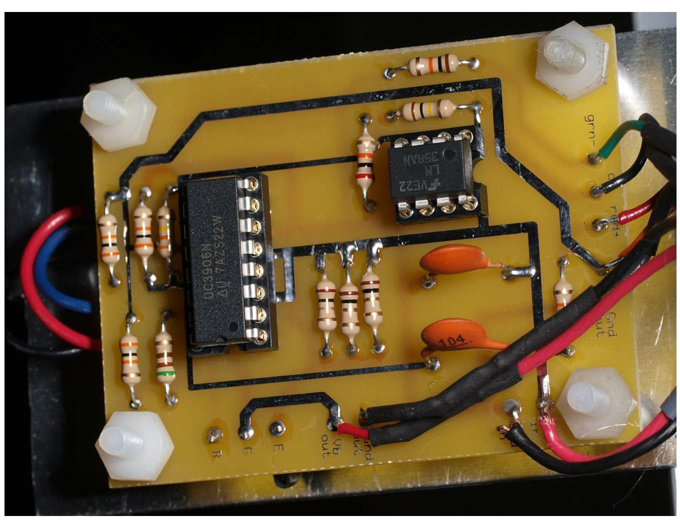

Figure 3 Lantern Charging Circuit

inside a wooden or metal box together with a commercially available charge controller – available for less than 30USD. Connectors for the PV panel, car battery and lanterns complete the assembly as shown in Figure 4. We are currently in the process of moving to a switched mode power supply since this offers a substantial increase in efficiency over the existing pass-transistor design. Although the circuit complexity increases, and thus the component count and opportunities for error, the increased efficiency available from a switched mode power supply far outweighs these considerations.

Figure 4 Central Charging Station with Lanterns

**Lantern**

Designing a rechargeable lantern is a much more formidable task than might be imagined. An electrical lantern comprises the functional blocks listed in Table 1 and illustrated in Figure 5. As drawn, the base housing represents bamboo, the red discs are clay and the light diffuser comes from a translucent plastic bottle containing fruit juice or rubbing alcohol. We have since modified the design and replaced the On/Off switch and dimmer potentiometer with a single three position switch – On (high brightness) : Off : On (low brightness) – in response to feedback from the pilot installations. We have also moved the LED from the top plate above the diffuser to the plate below the diffuser – thereby enabling the LED to be attached directly to its driver circuit board which is then securely attached to the housing – obviating the need for cables to run from the lower to the upper block.

Reasons for the choice of a lead acid battery have already been discussed: to prolong its life, a comparator is used to measure the battery potential against a predetermined reference – set to dictate the maximum depth of discharge. However, from the literature, setting a potential to represent a specific depth of discharge is not straightforward. The exact relationship between the temperature, depth of discharge, shelf life and number of charge cycles is not easy to ascertain and is further subject to uncertainty since it involves an electrochemical reaction within an environment which physically alters with time. We expect the batteries in these lanterns to have a useful life of about four years, based upon the fact that the lantern will need to be charged approximately once every four days.

Table 1: Components of an Electrically Rechargeable Lantern

| | |
|---|---|
| Electron to Photon Converter (LED) | Electrical Energy Storage System (Battery) |
| Light Distribution System (Optics) | Electrical Recharge System (PV Panel) |
| Light Control System (Switching Circuitry) | Mechanical Chassis (Housing) |

The efficiency, size and robustness of a LED far outweigh any advantages offered by a compact fluorescent bulb. In Figure 6, the light outputs from a selection of sources are plotted from which the superior light distribution of the kerosene lantern is clearly evident. It is very interesting to note that the lowly fantilla (a cotton wick immersed into shea nut oil) far outperforms a commercially available lantern manufactured in sub-Saharan Africa. This result illustrates so well the generally poor performance of the sub-standard products currently available. Apart from the virtually nonexistent illumination, the other common complaint about existing products is the short battery life – they commonly need to be replaced after only six months use.

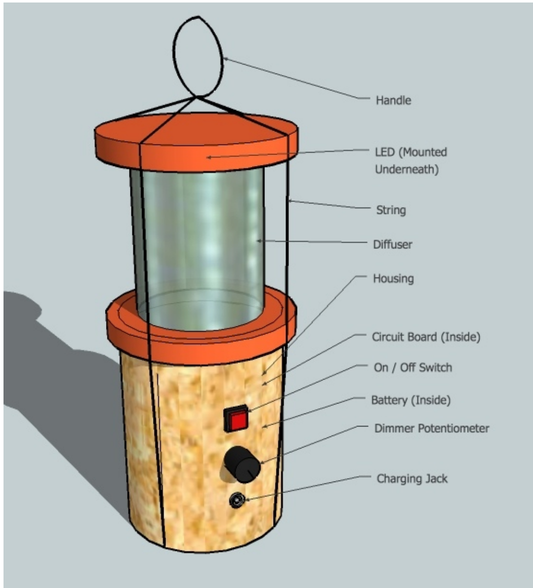


Figure 5 SociaLite Lantern

By far the greatest design challenge presented by the lantern is the geometry of an optical system for efficient light distribution. A major disadvantage of the LED is the highly directional, conical distribution of the light. To produce a pleasing diffuse light source we have investigated a range of distributed and non-distributed light scattering geometries ranging from gels containing small reflective platelets or air bubbles; to abraded Perspex hemispheres or rods; to crumpled aluminum foil – anything to scatter the highly directional light with the minimum insertion loss. To date, the best results have been obtained with translucent plastic bottles but we do not see this as an optimum result and are actively seeking alternative solutions. We still hope to be able to fabricate a multipurpose lantern whose illumination pattern can be optimized for reading and writing or for general purpose lighting – with minimal changes to the physical geometry of the optics.

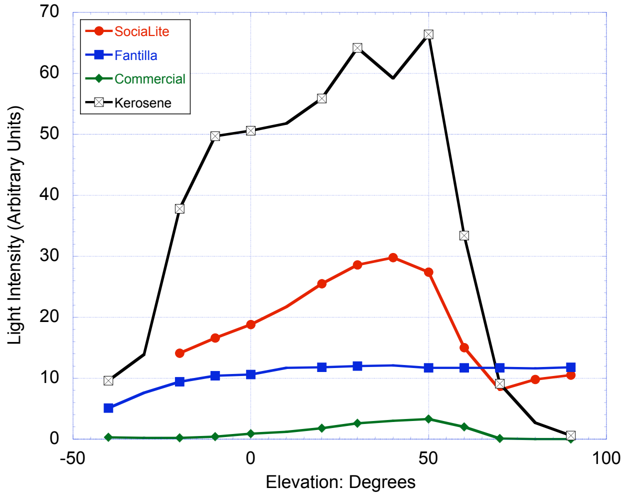


Figure 6 Light Distribution from Four Different Light Sources

## 4. SYSTEM IMPLEMENTATION

After the student teams had been presented with the challenge described earlier, direct guidance was kept to a minimum. Regular meetings were held at which the progress and direction of the design were monitored. In addition to conforming to the overall goals of the project, the reasoning behind each design decision or modification had to be explained to the satisfaction of the students and faculty present. The first lantern was both a triumph and a disaster: a triumph because the design encompassed the true elements of minimalist engineering and sustainability; a disaster because the device was extremely fragile and provided very poor illumination.

The first system was installed in the community of Nambeg – a small community near Jirapa in the Upper West region of Ghana. Prior to installation we sought their help with system development and they voted unanimously to work with us. This lighting system comprised three lanterns with control circuitry comprising little more than an off/on switch and a very rudimentary charging station comprising two US-64 panels and a 75Ah car battery. A major upgrade took place in January 2008 when a much improved charging station was installed and ten new lanterns delivered. During the visit we discovered that the lanterns were much sought after and the less than perfect arrangements for sharing had led to a number of physical disagreements.

The new lanterns are capable of running for approximately 20 hrs at full power and approximately ten times longer on the low power setting. If the lanterns are used for 5 – 6 hours a night, the batteries need to be charged every four days. Using HOMER, a free program available from NREL, we estimate that an 80W PV panel and 75Ah car battery can easily support a fifty lantern installation in Northern Ghana – and also accomodate the maximum six cloudy days in succession.

To date we have established five installations in remote, rural communities in Northern Ghana and Southern Rwanda from which to gather feedback about the uses of this technology and the robustness of the design; and to gather community input to the design, operation and maintenance of these systems. The information gained from our first two installations has provided critical input to development and made us aware of factors that we would not otherwise have considered. Experience with these installations has also demonstrated that communities are well capable of maintaining solar lighting systems – although it should not be inferred that everything went smoothly! We believe that part of the success is due to direct incorporation of the communities into the development process giving them ownership of, and buy-in to, the product – thereby releasing them from expectations of aid and handouts from Western donors.

An integral part of the design philosophy is that for the lighting system to succeed it must be a truly self-sustaining venture that is driven by the end user. Agencies in both the Developed and the Developing World are finally beginning to understand that aid is a waste of time (Moyo, 2009) and that true assistance is a partnership. During the summer of 2008, we took some lantern kits to Baazing – a small village north of Jirapa beyond the end of the dirt road – and asked the community to help us assemble their lanterns (see Figure 7). We taught them how to solder, what the different components looked like and so on. The outcome was truly inspiring – a community that had no electricity, no light and no solar panels was able to construct its own solar lighting system. We believe that this was a seminal event and fully supports our assertion that it is possible to establish assembly lines for “high-tech” products within remote, rural communities. They are now able to fabricate and repair their own lanterns.

From our experience in Baazing, we went on to develop a prototype assembly line for the fabrication of a entire lighting system – complete with instructions, tools and jigs. Two of these assembly lines have been installed in Ghana – one at Wa Polytechnic, the other at the Kwame Nkrumah University of Science and Technology in Kumasi. A third assembly line has been established at the National University of Rwanda in Butare. Working with students and faculty at these institutions, these prototype assembly lines are providing critical feedback and enabling this partnership to jointly develop a turnkey lighting system. Using a combination of diagrams, sketches, audio and video, we are in the process of developing comprehensive documentation for the fabrication of a rechargeable lantern, the base station charging circuitry, system installation, operation and maintenance.

Figure 7 Selection of Lanterns with Different Housings

All the imported components necessary for the construction of a fifty lantern solar lighting system will fit into a medium size duffle bag as shown in Figure 8: not included are the lantern housings, since these are derived from the materials to hand, and the batteries since these are sourced locally. The reasons for these choices are varied. The electronic components for the lighting system can more reliably be sourced from a country within which there exists reliable quality control. In conjunction, omitting the batteries saves a tremendous amount of weight and avoids the problem of shipping hazardous materials; omitting the lantern housings considerably reduces the volume whilst forcing the end user to contribute to the design.

In the longer term, the aim is to source an ever increasing number of components locally so reducing dependence on third parties for the supply of goods and simultaneously removing the extensive "red tape" that inevitably accompanies the importation of goods into a Developing Country. With a large market penetration, quality control of the components and packaging of kits for the lighting system will ultimately be undertaken in the user country.

Figure 8 Components for Self Assembled Lighting System

During the summer of 2009, we sold two systems and are using these to test our model for payment: a lump sum down on receipt of the system and weekly/monthly payment thereafter to recharge the batteries and simultaneously pay off the outstanding balance. Monies collected thereafter can be used to support system maintenance and go towards a fund that purchases new lantern batteries. When the foundations of the lighting system are in place, a recycling scheme will be established in which old batteries are replaced with new ones – the cost probably subsidized in part by the recharging payments.

## 5. CONCLUSION

We believe that we have proven the concept of a lighting system that can be delivered in kit form for self-assembly by the end user or someone close to. We also believe that we have demonstrated working prototypes of all the technical aspects of the proposed system and currently await the outcome of the financial/business exercises in progress. Looking to the near future, we are working with individuals, entrepreneurs and self-help groups in over twenty countries distributed across three continents to introduce lighting systems into their remote, rural communities.

Finally, it is worth noting that in Ghana, the Community Water and Sanitation Agency has been charging communities a proportion of the cost of a new borehole for many years. Whilst this means that some communities have yet to access to a borehole, the existing boreholes are well maintained and have not fallen into disrepair – they are treated with respect as a community resource. Our small experience to date suggests that a lighting system is accorded the same esteem.

## ACKNOWLEDGEMENTS

This work is partially supported by grants from the National Science Foundation (OISE #0553789), the National Collegiate Inventors and Innovators Alliance (ET-5572-08), and has benefitted from past awards from the US Environmental Protection Agency and a significant number of private donations including one from the American Tank and Vessel Company (Houston, Texas). We would especially like to thank Jennifer Keller Jackson (NCIIA) for her support and encouragement – it has proved an inspiration for us all. Many past and present Cooper Union students have contributed to this project: in particular, we would like to thank Dr. Nadia Pervez, Karen Del Aguila, Gaurav Namit, Anurag Panda, Nicholas Wong, Ian Jacobs, Leah Freed, Yoo Rhim Choi, Eric Zagorski, Linda McLaughlin, the students in Professor Cumberbatch's 2006 and 2007 EID101 sections, and his EID357 classes over the past four years.

We acknowledge the communities in Nambeg and Baazing (UWR Ghana) with whom we have worked and from whom we have learnt much. More recently, groups of students at Wa Polytechnic and the National University of Rwanda have built new systems which have been deployed in Tampala (UWR, Ghana) and the Muganza Sector, Gisagara District (Southern Province, Rwanda). Without the hard work, long hours, dedication and commitment of everyone mentioned and the hundred or more students who did the real work, this project would not have come to fruition.

We further acknowledge the significant input and interest from organizations and community groups in Ghana, Rwanda, Uganda (Uganda SPACE, Genice Jacobs), Burundi (Cyprien Mudenge), Nigeria, Peru, Democratic Republic of the Congo, Zambia, Tanzania, Cote d'Ivoire, Guatemala, Ecuador, Haiti, Togo, Kenya, India, Sierra Leone, Guinea Bisseau, Mali, Burkina Faso and Malawi.

## REFERENCES

Chambers, R. (1983) "Rural Development: Putting the Last First." London; New York, Longman.

Easterly, W. R. (2006) "The White Man's Burden: Why the West's Efforts to Aid the Rest Have Done so Much Ill and so Little Good." New York, Penguin Press.

Moyo, D. (2009) "Dead Aid: Why Aid is not Working and How There is a Better Way for Africa." New York, Farrar, Straus and Giroux.

Polak, P. (2008) "Out of Poverty: What Works When Traditional Approaches Fail." San Francisco, Calif., Berrett-Koehler.

Smillie, I. (2000) "Mastering the Machine Revisited: Poverty, Aid, and Technology." London, UK, ITDG Publishing.

Yunus, M. and K. Weber (2007) "Creating a World without Poverty: Social Business and the Future of Capitalism." New York, PublicAffairs.