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Challenges in Sustainability

Research Article

Mobile Open-Source Solar-Powered 3-D Printers for Distributed Manufacturing in Off-Grid Communities

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Abstract: Manufacturing in areas of the developing world that lack electricity severely restricts the technical sophistication of what is produced. More than a billion people with no access to electricity still have access to some imported higher-technologies; however, these often lack customization and often appropriateness for their community. Open source appropriate technology (OSAT) can overcome this challenge, but one of the key impediments to the more rapid development and distribution of OSAT is the lack of means of production beyond a specific technical complexity. This study designs and demonstrates the technical viability of two open-source mobile digital manufacturing facilities powered with solar photovoltaics, and capable of printing customizable OSAT in any community with access to sunlight. The first, designed for community use, such as in schools or makerspaces, is semi-mobile and capable of nearly continuous 3-D printing using RepRap technology, while also powering multiple computers. The second design, which can be completely packed into a standard suitcase, allows for specialist travel from community to community to provide the ability to custom manufacture OSAT as needed, anywhere. These designs not only bring the possibility of complex manufacturing and replacement part fabrication to isolated rural communities lacking access to the electric grid, but they also offer the opportunity to leap-frog the entire conventional manufacturing supply chain, while radically reducing both the cost and the environmental impact of products for developing communities.

Keywords: Appropriate Technology; Distributed Manufacturing; Open Source Hardware; Photovoltaic; Solar Energy; 3D-Printing

1. Introduction

Modern energy access is still far from universal, as 1.4 billion people lack access to electricity [1], which directly contributes to multidimensional poverty throughout these regions [2]. Although two-fifths of South Asia's population, primarily living in rural areas, have no access to the grid, more than three quarters of the population of Sub-Saharan Africa (587 million people) in both rural and urban areas are without electricity [3]. This situation appears to be static as rural electrification is a major challenge [4] and as the International Energy Agency (IEA) estimates that if rural electrification continues at the present rate, electricity access will only keep pace with population growth until 2030 [1]. Although some manufacturing occurs in communities without access to electricity, the technical sophistication of what is produced is limited. People with no access to electricity still have access to some higher-technologies, which are imported and lack all customization and often appropriateness for the community. Considering only energy-related devices, for example, throughout the developing world there are broken windmills and micro-hydropower installations, empty biogas pits, rusting charcoal kilns, and unused solar cookers [5] or tractors and water pumps in poor condition [6]. Often the local failure of such technologies, which are employed in many communities, is the lack of appropriateness for a specific community (e.g. difficulties in access to parts and capacity to perform repairs, evolutionary capacity of the technology, predetermining risk factors) [6–8]. Thus there is a need to ensure appropriate technology (AT) is used, this can be defined as those technologies that are easily and economically put to use from resources readily available to local communities, whose needs they meet [9]. The technologies must also comply with environmental, cultural, economic, and educational resource constraints in the local community [9]. Earlier definitions of AT have recently been extended by Sianipar et al. to include technical, economic, environmental, social, cultural, judicial, and political specifications [8]. To meet these requirements the diffusion of information technologies (e.g. cell phones and the Internet) has enabled a commons-based open design or 'open source' method to accelerate development of AT [10–12]. In parallel to the open source movement in software, open source appropriate technology (OSAT) is gaining momentum as it allows technology users to be developers simultaneously and share the open "source code" of their physical AT designs, and to use this ability as a science and engineering education aid [13–20]. OSAT is AT that is shared digitally and developed using OS principles. Thus, rather than computer programs, the "source code" for AT is material lists, directions, specifications, designs, 3-D CAD, techniques, and scientific theories needed to build, operate, and maintain it. One of the key impediments to the more rapid development of OSAT is the lack of means of production of open source technologies beyond a specific technical complexity.

This barrier is being challenged by the rise of open manufacturing with open-source 3-D printers [21], affordable versions of which are capable of replicating any three dimensional object in a number of polymers and resins [22–25]. The most striking of these 3-D printers is the RepRap, so named because it can fabricate roughly half of its own components and is thus on the path of becoming a self-replicating rapid prototyper [23–24]. Recent work has shown enormous potential for open-source 3-D printers to assist in driving sustainable development via digital fabrication and customization [26]. For example, there is currently a collection of open source designs useful for sustainable development [27] including peristaltic pumps, hemostats, and water wheels on Thingiverse, a repository of digital designs of real physical objects [28–30]. Most importantly RepRaps allow users in any location the ability to custom manufacture products that meet their own needs and desires.

In order for rural communities to have access to the benefits of 3-D printing of OSAT they will need electric power from locally available renewable resources such as solar photovoltaic (PV) technology which converts sunlight directly into electricity. PV has already been shown to be a technically viable, environmentally benign, socially-acceptable and increasingly economical method of providing electricity to both on grid and remote communities all over the world [31–37]. Solar PV-generated electricity is particularly well suited for small scale off-grid applications because of the relatively modest power draws of open-source 3-D printers, and it will be addressed here.

This paper provides a description and analysis of i) mobile community-scale and ii) ultra-portable open-source solar-powered 3-D printers including component summary, testing procedures, and an analysis of energy performance. The devices were tested using three case study prints of varying complexity appropriate for developing community applications, while measuring electricity consumption. Results of this preliminary proof of concept and technical evaluation of the use of solar PV to power mobile RepRaps for distributed customized manufacturing are evaluated and conclusions are drawn.

2. Methods

2.1. RepRap Background

RepRaps can currently print with ABS, polycaprolactone, polyactic acid (PLA), and HDPE among other plastics and generally cost between \$30–50 kg^{-1} [23,25]. PLA, which is used here for tests, fits the definition of AT as it is derived from renewable sources, is recyclable and bio-degradable. In addition, printed PLA with a RepRap has been shown to be as strong as commercial prints [38]. The extruder intakes a filament of the working material, heats it, and extrudes it through a nozzle. The printer uses a three co-ordinate system, where each axis involves a stepper motor that makes the axis move and a limit switch which prevents further movement along the axis. The printing process uses sequential layer deposition, where the extruder nozzle deposits a 2-D layer of the working material, then the Z (vertical) axis lowers, and the extruder deposits another layer on top of the first. In this way it can build three dimensional models from a series of two dimensional layers. It should be noted that other heads are under development that would allow for a greater range of deposition materials [23,25,39–42]. It should be pointed out here that any of the RepRap class of 3-D printers can be deemed appropriate for this application. The FoldaRap was chosen as the final prototype here as it is commercially available. It is a RepRap that folds down, as its name implies, into a small footprint and is thus relatively easy to transport. Today there are many easily transported RepRaps.

2.2. Power Requirements

Here only standard RepRap solid polymer filament extruders are considered. Their power requirements based on a number of options are shown in Table 1.

The total power necessary will also be determined by the processing options as shown in Table 2. Power was measured with a multimeter (± 0.2%).

Table 1. Power requirements of RepRap variants.

RepRap Name	Power printing (W)	Power heating (W) Time (min^{-1})*
LulzBot Mendel	35 W	140 W 1–2 min^{-1}
Prusa Mendel	37 W	130 W 1–2 min^{-1}
FoldaRap	40 W	135 W 1–2 min^{-1}

Note: it should be noted that the tests in this study were performed on a heated bed to represent a worst case scenario. The heated bed can be avoided by printing on blue painters' tape with PLA or with a glue-stick on glass, but such appropriate surfaces have not been found for all plastics.

Table 2. 3-D printer processing power requirements.

Option	Price	Power (W)	Operating System	Notes/References
Raspberry Pi [43]	$35 (+monitor)	3 W (+monitor draw)	Linux	Pros: very inexpensive, large online community support, RepRap software available on Linux Cons: potentially long delivery times
APC 8750 [44]	$49 (+monitor)	13 W (+monitor draw)	Android 2.3	Pros: larger processor than Raspberry Pi, Cons: no available software, would have to write new program, not yet readily available, high power consumption
Efika MX Smartbook [45]	$199	3 W–6 W	Linux	Pros: runs Linux, battery life of up to 7 h so no extra power draw, Wifi & 3G for downloading new designs, lowest cost for highest functionality Cons: higher cost
Control through cell phone via Bluetooth [46]	$29 (with existing cell)	1 mW–5 W	Android	Pros: cell phones widespread, "cool" factor Cons: current software needs improvement, can only print designs already in hand
Use only an SD card slot [47]	$35	0 W	N/A	Pros: ultra low power, very low cost Cons: can only print designs already in hand, no community design
Tablet	$150–500	7.5 W–10 W	Varies	Pros: no extra power draw on system, readily available Cons: higher cost

Option	Price	Power (W)	Operating System	Notes/References
OLPC [48]	$100–200	2 W	Linux	Pros: large user community, already scaled in developing world Cons: expense, difficulty running some software

2.3. Designs

Here two types of designs are considered: i) mobile community-scale and ii) ultra-portable open-source solar-powered 3-D printers.

2.3.1. Community-Scale Mobile 3-D Printing

The community-scaled device is designed to be appropriate for a school or a community center that enables many shared users in a community to utilize the equipment. The first portable solar powered RepRap was a Mendel variant using off-the-shelf components [49] and running RAMPS1.3 with an SD card add-on which allowed it to save power by printing without a computer connection. This system was designed for heavy usage. The 2 x 220 W PV panels, and 4 x 120 Ah batteries give the user 35 hours of printing with a single charge. The system uses an inverter to convert the DC energy from the PV and batteries to a standard AC signal. A standard power bar can be hooked up to the inverter, so it can run/charge multiple laptops or printers at once. The frames of the solar panels are reinforced and hinged together so that the faces of the PV modules fold together to prevent damage during transport. There are adjustable, drop-down legs affixed to the modules, so they can be angled accordingly for maximum sun exposure. The community-scale PV+RepRap system is shown in Figure 1a and the design schematics are shown in Figure 1b. The complete bill of materials and assembly is documented here in [50].

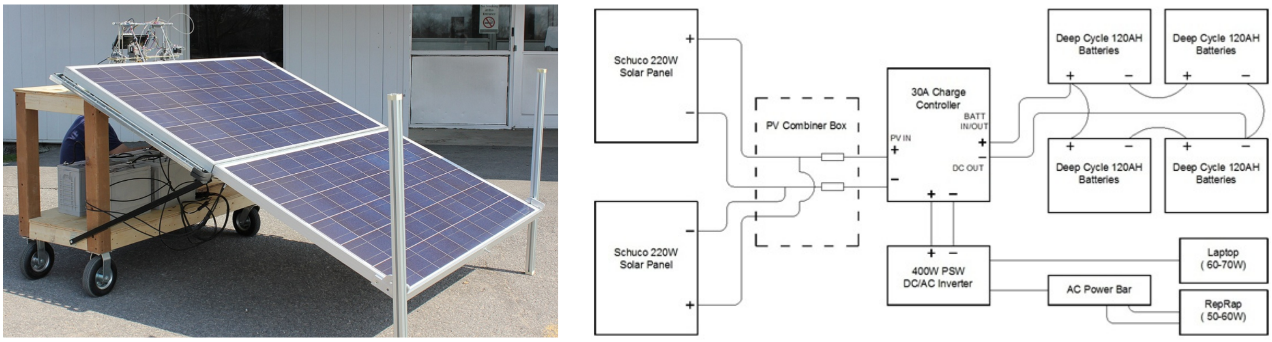

Figure 1. a) Community-scale PV-powered open-source RepRap 3-D printer system for off-grid community use and b) the basic schematic design. The PV are connected in parallel; a combiner box is used to combine and drive the DC supply towards a 30 A charge controller, which maintains the controlled charging and discharging of the batteries. The batteries are connected in two parallel lines with each line containing two unit cells in series. During charging periods four 120 AH batteries are fed DC current while discharging continues to power the RepRap and the laptop through a DC/AC inverter.

2.3.2. Community-Scale Mobile 3-D Printing

An ultra-portable open-source solar-powered 3-D printer has also been designed. This system can be easily transported in a suitcase and is intended to provide complete mobility so as those visiting an isolated community (e.g. doctors) can bring it with them to print necessary products on site in the field. Although not solar powered, a team from MIT has already reported on developing a suitcase 3-D printer [51] and there are other portable 3-D printers currently on the market, including Printrbot Jr (v2), Portabee, Bukito Portable, Taz, Tobeca (which comes in a case) and the Foldarap. Here the ultra-portable system is based around the FoldaRap shown in Figure 2a. It is a RepRap variant, designed by French engineer, Emmanuel Gilloz [52]. The FoldaRap is built on an extruded aluminum base that is designed to fold into a 350 x 210 x 100 mm frame. The ultra-portable solar-powered suitcase 3-D printer is shown packed and deployed in Figures 2b and c, respectively. The design schematics are shown in Figure 2d.

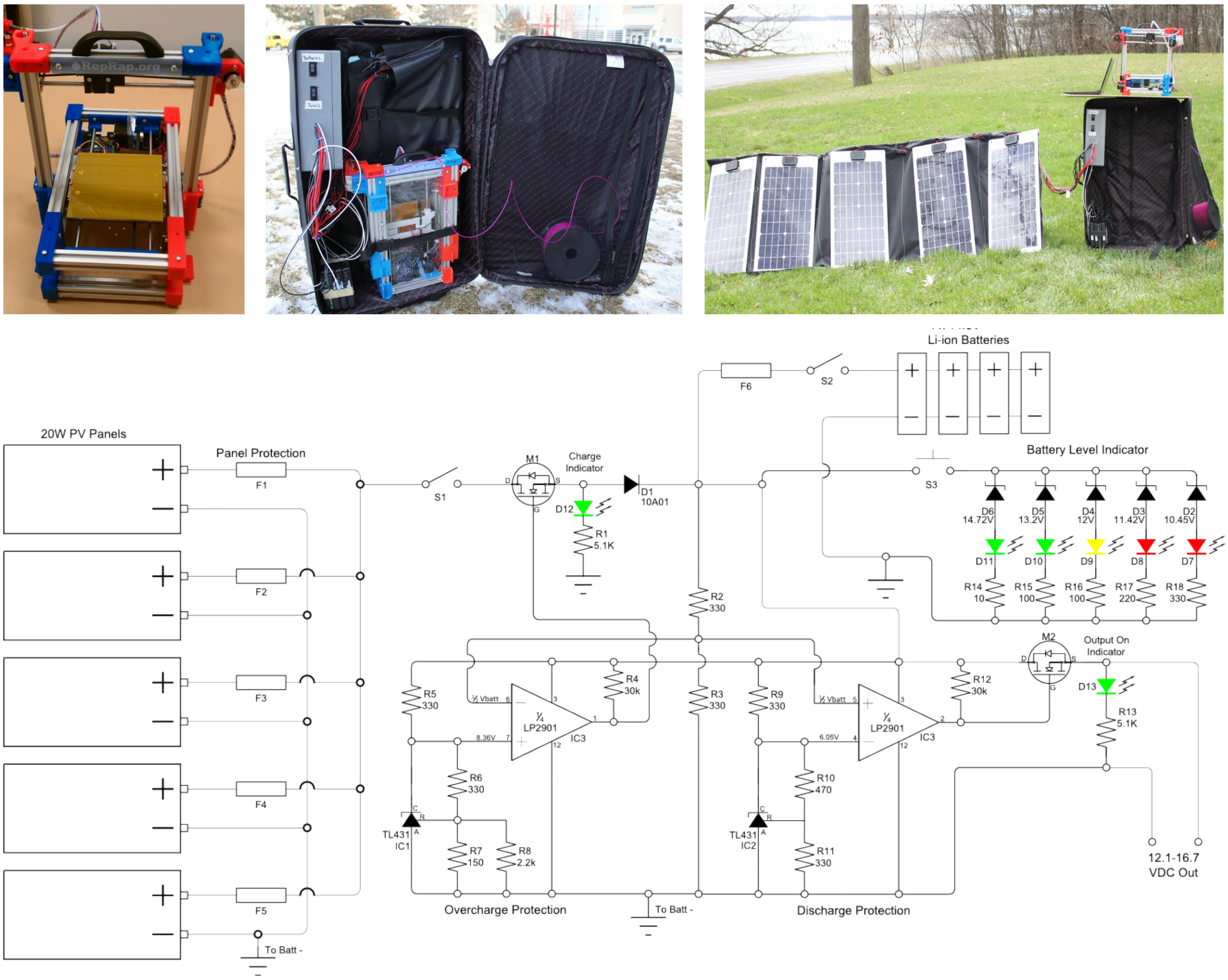

Figure 2. a) Foldarap, b) ultra-portable PV-powered open-source suitcase Foldarap 3-D printer packed, c) deployed for printing, and d) the circuit diagram. An ATmega328 based Arduino Uno microcontroller board is employed to control the charging unit. A current sensor, a temperature sensor and a shunt circuit are provided to keep records and avoid unwanted damage to circuit components. A 16 x 2 LCD display is used to monitor mode of operation. No DC/AC inverter is included; instead a DC/DC charge controller is used. The charge controller follows the voltage divider rule in order to control the supply voltage, and feeds steady current to the Foldarap.

The Efika MX Smartbook, an 'ultra-portable' notebook, was chosen to control the printer. Its power runs at an average of 3 W, compared to the standard 60 W from other commercial notebooks. The Smartbook's battery can easily last 7 hours on a single charge. Running the printer off from an SD card was considered, but in this case only parts that were already stored on the SD card would be printable. To ensure new parts could be designed and printed on site, a computer was necessary. Although the Smartbook was chosen for this project, it is not considered a must-buy component if the builder already has a laptop with sufficient battery life.

To achieve full mobility in this model light-weight, semi-flexible PV modules were used. At 0.95 kg a piece, these modules greatly reduce the size of component that comprises the largest footprint on the community-scale model. The PV modules are comprised of high-efficiency mono-crystalline silicon cells. The bulk and weight are reduced by placing the cells on an aluminum backing, and coating them with a clear gel, replacing the traditional large aluminum frame and glass panel front. This system uses five 20 W modules, to give 100 W at just over 10 lb. The modules are mounted on a durable nylon fabric enclosure to prevent damage during transport.

The other main weight reduction from the community model is in the batteries. Lithium-Ion batteries are used in the portable model for a high storage density in a lightweight package. Although there are denser battery chemistries emerging on the market, Li-ion best fits the goal of a low-cost system. This system uses four 14.8 V 6600 mAh laptop batteries. An inverter was not used in this system, as multi printer/laptop functionality was not required. The circuit is designed to solely run the printer, which requires 12–30 VDC. The complete bill of materials and assembly instructions are available at [53].

2.4. Measurements and Case Study Designs

The rate of battery charging with the PV monitored and correlated with detailed methods that had previously been used to determine solar flux using Open Solar Outdoors Test Field equipment and systems [54] and the state of charge of the battery were measured. Three representative designs were used for testing, as shown in Figures 3a, b and c: 1) avocado pit germination holder [55], 2) cross tweezers [56] battery terminal separator [57]. The latter was used in the construction of the ultra-portable solar-powered suitcase printer from Figure 2. The volumes of plastic used were 8.96 cm^3, 3.47 cm^3, 6.91 cm^3 respectively. All of the prints were downloaded from Thingiverse under CC-BY or public domain licenses, a repository of open source designs that currently with over 455,000 designs and is growing exponentially [58], and were chosen from a selection of designs with the OSAT tag. It should be pointed out here that in general Thingiverse licenses would not offer any application problems in development. The one potential exception is creative commons non-commercial licenses, which could still be printed by community members although they could not be sold. The prints were chosen for varied print difficulty, times and volumes. The cross tweezers being one of the smaller end of expected print times, and the battery holder being a standard print. The cross tweezers require a fine enough resolution to test the accuracy of the printer. The following slicer settings were used for the experiments: 2 perimeters, 4 horizontal shells (2 top, 2 bottom), 35% infill, 1.7 mm PLA, and 200° C for the hotend and 55° C bed temperatures, respectively.

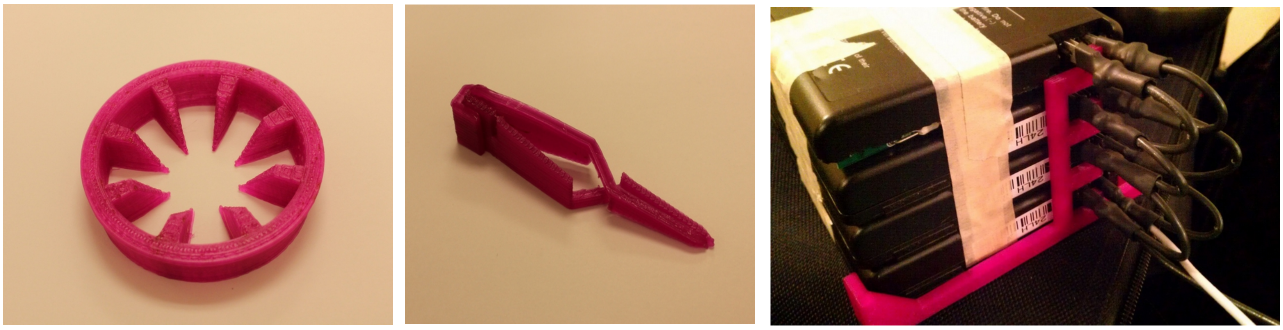

Figure 3. OSAT printed on the ultra-portable PV-powered open-source suitcase Foldarap 3-D printer a) avocado pit germination holder, b) cross tweezers and c) battery terminal separator.

3. Results and Discussion

The three case study prints were successfully printed on both device designs and example prints are shown in in Figure 3. The size of the battery bank in the first design ensured that hours of continuous printing would be available to a community every day there was adequate sunlight. The much smaller battery bank needed for ultra-portability in the second design, however only enables a few prints per day on one charge. The actual parts able to be printed are determined the solar flux availability, the fill density and slicing settings, and the size and geometric complexity (more complex parts take longer and use more energy to print as the head moves without printing). Table 3 summarizes the state of charge of the batteries and print time on the ultra-portable printer from Figure 2. The heated bed and extruder only took an average of 2 minutes to get to target printing temperatures on the suitcase printer. Once printing, an average of 40 W was used, decreasing the expected amount of energy use and increasing the length of time the batteries can last on a single charge. The cross tweezers came out with a slight warp, as one end started lifting from the bed during the print. This might have been prevented by using a 60° C bed temperature rather than the 55° C that was used.

Table 3. Print time and change in charge state of test case study 3-D prints.

Case	Change in State of Charge in Percent	Print Time (min)
1 Avocado Pit Germination Holder	18.1	49
2 Cross-Tweezers	12.9	34
3 Battery Terminal Separator	17.5	50

The results of this study are applicable to any off-grid community in the world with access to sunlight. Both the community-scale and individual suitcase portable PV-powered RepRaps were found to be functional and viable for digitally fabricating custom OSAT on location. The ability to easily fabricate custom and complex parts or products at exceptionally low-cost offers people anywhere in the world the ability to print themselves out of poverty as they can print items to meet their own needs, those of their community, and export items to sell [58]. As the RepRaps are capable of printing both their own components for replacement and are able to upgrade themselves as the global community improves the design, RepRaps have an extended life cycle and are appropriate for most communities.

The related work with RecycleBots, which turn waste plastic into 3-D printing filament, can be viewed as a major enabling technology as it allows local materials to be used in the production of high-value 3-D printer parts, with lower costs and less environmental impact [59–63]. Plastic waste is common in many developing communities [64,65] and informal waste recycling is sometimes conducted as an economic activity [66]. ProtoPrint in India is already using waste pickers to recycle plastic into 3-D filament as part of a social entrepreneurship program. Similar efforts are underway with the Ethical Filament Foundation and Plastic Bank's social filament program. For regions, with no access to waste plastic, further work is needed in biopolymer reactors to produce PLA from agricultural waste. Similarly, access to the electronics in parts of the developing world may be limited. Thus, there is a generalizable risk of repeating the past problems with broken equipment meant for development (e.g. pump parts) by creating a new problem of broken 3-D printers. Future work is needed in developing RepRaps capable of fixing and printing electronics components. It should be pointed out here that this is not a complete solution, but a path towards sustainable development that is still under construction.

The initial costs of the community and suitcase systems as designed here were $2,500 and $1,300 respectively. These costs are still substantial, particularly for the majority of the developing world. These were prototypes and the costs of the systems can be expected to drop considerably for any replication of the systems for two reasons. First the cost of PV has dropped from the $1.59 W^{-1} for which the community panels were purchased and $1.90 W^{-1} for the suitcase panels to under $0.65/W for PV on the international market. Similarly, the cost of the open-source 3-D printers has been reduced from the start of this study at $800 and $600 for the Mendell RepRap and Foldarap to currently about $550 for a Michigan Tech HS Prusa RepRap design [58] and under $500 for a MOST Delta RepRap [67]. Both of these major costs appear to be able to continue to fall. The value of owning or having access to a printer is also increasing exponentially along with the number of open source designs—as producing only 20 common objects with a RepRap in 25 hours of printing at home could save consumers $300–$2000 [58]. It should be pointed out that this study [58] is for wealthy developed countries. Most of the products printed are not available in areas of the developing world and of questionable utility for sustainable development. For developing communities, printed items that bring high value would need to be identified and designed. In addition to the high economic return from deploying PV+RepRap systems for distributed manufacturing, there are also substantial reductions in the environmental impact of manufacturing using this process rather than standard manufacturing [60–62].

Both RepRaps and Recyclebots are open-source technologies where hundreds of people throughout the world are collaborating to rapidly improve the technology and provide an incredibly fast growing selection of products to print with them. This provides the potential of a major paradigm shift in how industry works, which encourages local and even home-made manufacturing of a rapidly increasing selection of highly sophisticated and valuable products. These technologies and the open source paradigm hold the promise of creating enormous wealth for those in developed and developing communities. Perhaps the most immediate change for the developing world will be access to high-quality customized scientific equipment at unprecedented low costs (e.g. reduction by a factor of 100 in the costs of lab supplies and instrumentation) [15,16]. As this becomes commonplace there will be an accelerating positive feedback loop—the more scientists participate the faster technical problems will be solved and the more value will be created for everyone.

4. Future Work

There are several areas of future work that need to be addressed. First, continual reductions in the energy consumption of RepRaps will reduce the size and cost of the PV and battery storage systems for both designs. There has been preliminary work into printing with either a variable area heated bed or printing without a heated bed; the heated bed is the system's major energy draw and needs to be considered in more detail. In addition, a reduction in energy use is possible through the removal of all AC-DC conversions by avoiding standard computer power supplies. The design methodology used here was not formalized and thus the overall design can be improved in the future by following focused design methodologies such as Ecodesign [68,69] or Design for Sustainability [70] and, rather than using the PV-powered RepRap as only a means to manufacture AT, begin to specifically design it as AT itself [71].

This study should also be repeated with recycled waste plastic as several commercial RecycleBots are maturing and the concept of ethical filament is expanding worldwide. The RecycleBot and accompanying shredder/grinders will also need to be adapted for off-grid use with PV power. There is a large collection of designs and the beginnings of open-source digital OSAT designs, but far more work is needed to have printable designs to meet all of the needs of the world's people. Future field work could interview people living in a wide range of developing communities to find out what the most valuable and relevant OSAT prints are in different geographic regions. Considerable work is needed here, but it is also possible for relatively modest contributions of CAD for OSAT to have a major impact on communities all over the world. This work is now being completed largely by volunteers and hobbyists within the 'maker' movement. However, there is also a business opportunity for companies to profit from an open-source hardware paradigm paralleling the open source software movement that has led, for example, to RedHat, which is a $1 billion software company that distributes free software. In particular, companies that sell consumables or 3-D printer components, such as hot ends, should consider open-sourcing the designs for the products that drive the demand in the consumables and move them into new markets. Finally, in order to minimize costs while ensuring optimized designs, all of the components of the system need to be completely open source, including the possibility for printable PV [72] and a fully open source laptop.

5. Conclusions

This study designed and demonstrated the technical viability of two open-source mobile solar photovoltaic digital manufacturing facilities. The first, designed for community use such as in schools, is semi-mobile and capable of nearly continuous 3-D printing using RepRap technology while also powering multiple computers. The second design, which can be completely packed in a standard suitcase, is intended for specialist travel from community to community in the developing world to provide the ability to custom manufacture open source appropriate technology as needed, anywhere. These designs not only bring the ability to complete complex manufacturing and replacement part fabrication, to isolated rural communities lacking access to the electric grid, but they also offer the opportunity to leap frog the entire conventional manufacturing supply chain while radically reducing the environmental impact of production.

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