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High-Efficiency Solar-Powered 3-D Printers for Sustainable Development

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Abstract: The release of the open source 3-D printer known as the RepRap (a self-Replicating Rapid prototyper) resulted in the potential for distributed manufacturing of products for significantly lower costs than conventional manufacturing. This development, coupled with open source-appropriate technology (OSAT), has enabled the opportunity for 3-D printers to be used for sustainable development. In this context, OSAT provides the opportunity to modify and improve the physical designs of their printers and desired digitally-shared objects. However, these 3-D printers require electricity while more than a billion people still lack electricity. To enable the utilization of RepRaps in off-grid communities, solar photovoltaic (PV)-powered mobile systems have been developed, but recent improvements in novel delta-style 3-D printer designs allows for reduced costs and improved performance. This study builds on these innovations to develop and experimentally validate a mobile solar-PV-powered delta 3-D printer system. It is designed to run the RepRap 3-D printer regardless of solar flux. The electrical system design is tested outdoors for operating conditions: (1) PV charging battery and running 3-D printer; (2) printing under low insolation; (3) battery powering the 3-D printer alone; (4) PV charging the battery only; and (5) battery fully charged with PV-powered 3-D printing. The results show the system performed as required under all conditions providing feasibility for adoption in off-grid rural communities. 3-D printers powered by affordable mobile PV solar systems have a great potential to reduce poverty through employment creation, as well as ensuring a constant supply of scarce products for isolated communities.

Keywords: solar energy; photovoltaic; distributed manufacturing; appropriate technology; 3-D printing; off-grid; renewable energy; sustainable development

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1. Introduction

Additive manufacturing, also commonly known as 3-D printing, involves the use of both sintering- and extrusion-based processes to synthesize three-dimensional objects by depositing successive layers from a 3-D model [1–4]. This technology presents the capability of producing objects of different geometries or shapes, using different materials, such as polymers [5], free-standing liquid metals [6,7], solid metals [8,9], ceramics, clays, epoxy resin [10], and even living cells [11] and organs [12]. The introduction into the market of the RepRap (a self-Replicating Rapid prototyper) as the first free and open source 3-D printer released under the GNU General Public License led to the rapid technical evolution of RepRap 3-D printers [13–16]. This type of 3-D printer generally uses a fused filament fabrication (FFF) with thermopolymers. The free and open source hardware (FOSH) nature of the project led to explosive growth in the number of 3-D printing firms competing in the 3-D printing market, which reduced the costs of 3-D printers form more than $20,000 to below $1,000 within a few years [4,17]. These 3-D printers allow distributed manufacturing of products for significantly lower costs than conventionally-manufactured products [18,19]. Thus, the declining prices of 3-D printers, together with parallel development of open source-appropriate technology (OSAT) [20–22], has enabled the opportunity for 3-D printers to be used for sustainable development in many impoverished areas of the world [21,23–26]. OSAT can vary in complexity from high-end medical equipment or simple agricultural tools. OSAT presents the users with the opportunity to modify and improve the physical designs of their printers in line with their needs resulting in explosive mushrooming of hardware developers [22]. Ideally, OSAT comes with a comprehensive bill of materials and easy to understand instructions on the development process of the object allowing users to both easily build and improve on the designs. However, these 3-D printers require electricity, and according to the International Energy Agency (IEA), 1.3 billion people worldwide are without access to electricity [27]. IEA predicts that by 2030 population growth particularly in sub-Saharan Africa will surpass the pace of electricity access, resulting in 75% of the population of sub-Sahara Africa not having access to electricity by 2040 [27]. To enable the utilization of RepRaps in such isolated, off-grid communities, solar photovoltaic (PV)-powered mobile systems have been developed [28]. These previously-designed systems powered energy-intensive Cartesian-based RepRap 3-D printers (Prusa Mendel RepRap and the Fold-a-Rap) with heated-print beds [29]. Improvements in print bed surface treatment, the adoption of low temperature filament materials, such as biodegradable polylactic acid (PLA), decreased the number of stepper motors in novel 3-D printers designs (MOST delta [10]) and has enabled the elimination of the heated bed, resulting in a drastic reduction of printer power consumption.

In this study a mobile solar-PV-powered 3-D MOST-delta printer system was designed and experimentally validated. It is designed to provide a constant power regardless of solar flux to run the RepRap 3-D printer during operation. The open source electric control systems enables the 3-D printer to be autonomously powered from a battery when the PV modules are not supplying enough power, and then switch to charging the battery whenever there is excess power. Buck converters are used to control the voltage from the PV modules and the battery, while simplifying the electrical design compared to previous work. The electrical system design is tested outdoors for different operating conditions, covering five possible situations: (1) PV charging the battery and driving the 3-D printer; (2) printing under low insolation; (3) battery powering the 3-D printer with no PV; (4) PV charging the battery only (no printing); and (5) battery fully charged and the PV powering the 3D-printer. Results are discussed and conclusions from the experimental data are reported in this study.

2. Methods

2.1. System Design

The power supply/ battery charging system design is modified from the simulations developed by Khan *et al.* [29]. System sizing was done to achieve a system capable of powering the 3-D printer whenever PV modules are under sufficient illumination. The system should, however, be able to route the excess power towards charging the battery whenever the total power supplied by the PV modules exceeds the power required for printing. The battery used was a polymer Li-ion rechargeable battery pack (14.8 V, 20 Ah) which comes with an overcharge protection circuit enabling it to serve as an energy backup/reserve during low/no light conditions. The systems is optimized to operate in three different modes

(i) PV-only mode operation: In this mode, the PV modules supply enough power to meet the 3-D printer energy requirements. It is during this mode that the battery charging occurs, but only during instances when the PV modules power exceeds the printer load.

(ii) Mixed-mode operation; Both the PV modules and the battery power the printer. Usually this occurs when the illumination on the PV modules drops to level such that they can no longer provide the required power to drive the load. The battery converter responds by reversing its mode from charge to discharge mode and, by so doing, providing the power needed to compensate for the drop in PV module power.

(iii) Battery-only mode: The battery autonomously runs the printer. This happens if printing is done during the night or low light conditions. Total period of autonomy is dependent on the battery size and initial charge, and can be predicted for any system design.

Stand-alone PV power system modeling was performed earlier using MATLAB/Simulink 2014 [29]. The model was guided by predefined system performance factors under different operating conditions, one of the major requirements being the capability of the system to run on battery power in cases where the PV power is not available or sufficient to run the 3-D printer. The change-over period from PV to the battery has to occur instantaneously (about 0.05 s) to ensure uninterrupted 3-D printing. Figure 1 represents the model design for the stand-alone PV power system with dynamic response capabilities for quality 3-D printing experience when integrated with the MOST-delta 3D printer.

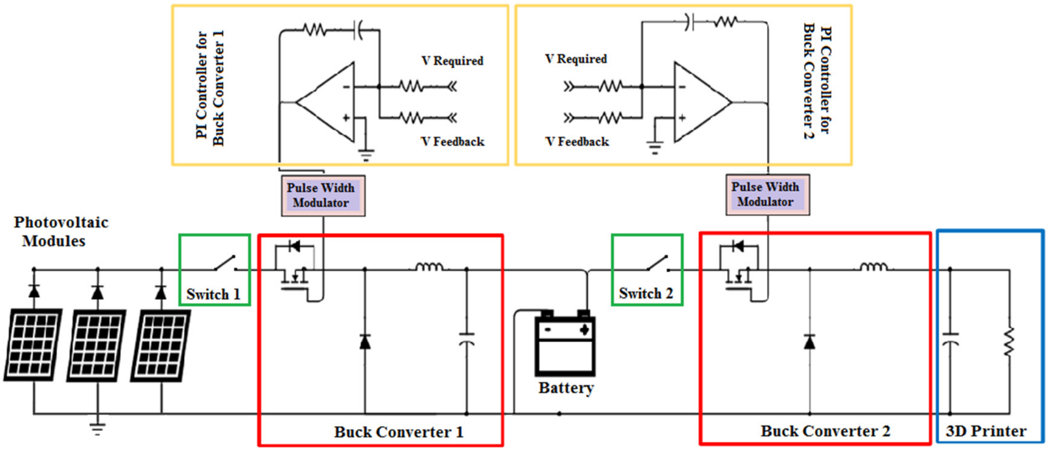

Figure 1. Schematic of power supply/battery charging stand-alone PV System for a MOST-delta RepRap 3-D printer for showing the arrangement of the PV modules, Buck converters, and the battery.

The MOST Delta RepRap printer [10,30] is a conglomeration of four stepper motors controlled by a Melzi [31] motor drive controller based on the Arduino architecture and a resistively-heated hot end with temperature feedback and position feedback from end stop mechanical switches, as seen in Figure 2.

The physical system design (Figure 3) was guided by the simulated model in Figure 1, where the PV modules are connected to Buck Converter 1, with the power flow being controlled by the Switch 1. There is a protection diode between each photovoltaic module of the solar array and the first buck converter. This prevents the flow of current back to the PV and the converter when the PV-module's voltage drops below the battery voltage. Buck Converter 1 is operated by a PI (proportional-integral) voltage controller which provides a duty cycle signal to a pulse width modulator. The output of buck Converter 1 feeds the battery, and also serves as the input of the second buck converter via Switch 2. The output of the second converter (which, just like the first converter, is also PI controlled) serves as the power input to the 3D printer load. Both converters are of non-isolated topology, requiring less switching devices compared to the isolated topology converters [32–34]. Overall, the choice of the buck converters used in this study was influenced by their efficiency, non-complex structures, cost, and availability.

The bill of materials shown in Appendix provides the components for the electronics that were assembled as shown in Figure 3.

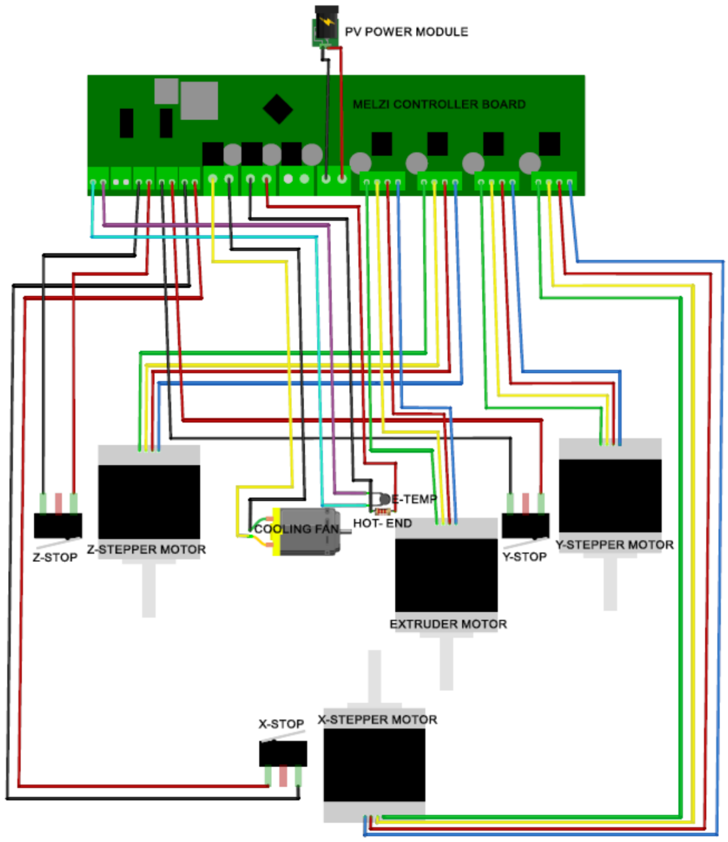

Figure 2. Fritzing schematic electronic diagram of MOST Delta RepRap.

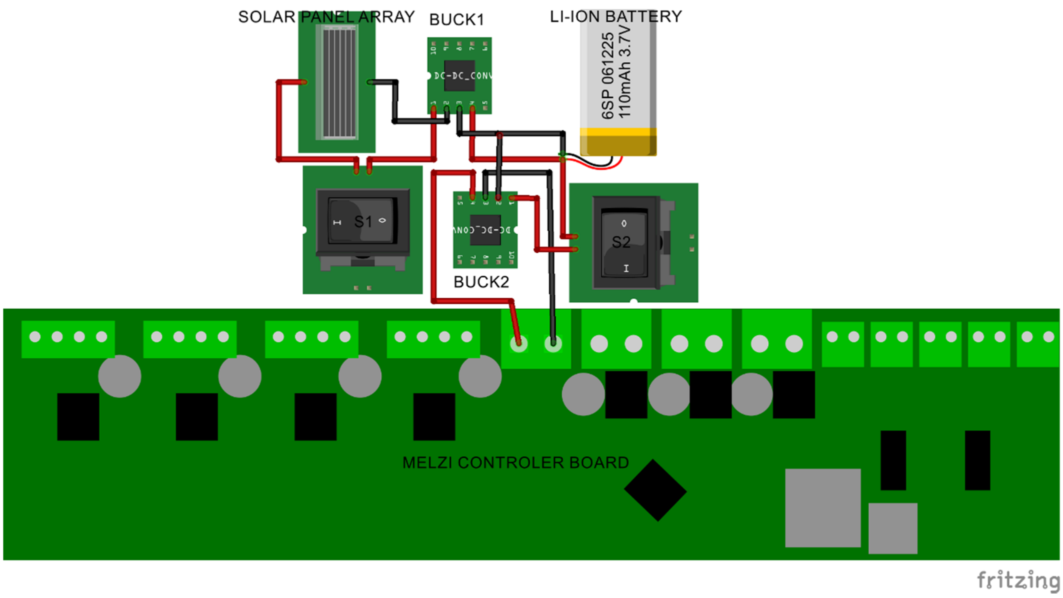

Figure 3. Wiring diagram of the power circuit.

2.2. System Integration

The stand-alone PV power system was integrated to a MOST Delta RepRap printer and print test runs were conducted to validate the physical design. The AC power pack for this printer is rated at 5 A and 12 V, making the maximum power rating to be 60 W. Print test runs showed the voltage and maximum power requirements of the printer to be 12 V and 48 W, respectively, and the standard printing power requirements for the MOST Delta RepRap was observed to be 37 W. The converters connected between the solar module, battery, and the 3-D printer have to regulate the output voltage to match the measured printer requirement. Since the system should be able to print while being charged, the PV modules should be rated at least 48 W to meet the requirement of the printer and route the excess power to charge the battery when the printer is not operating at its maximum rating. Since most PV modules currently on the market rated at 50 W or more have a voltage rating of at least 20 V, the use of converters to regulate the voltage of the PV module down to match the printer requirement is necessary. Two buck converters were preferred to a buck and boost combination because of the simplification of implementation and availability in the market. Furthermore, the use of two buck converters meant that the battery voltage had to be an intermediate value between 12 V and 20 V. Thus, a 4S Li-Ion battery pack with operation voltage range from 14.8 V to 16.8 V was acquired for this project design since its entire operating region of the battery pack is higher than the load requirement.

In addition to the electronic components, the RepRap itself was used to provide a conversion kit which was designed in OpenSCAD, a parametric open-source script-based solid modeling program. These scripts are available [35], and can be customized for other sizes or styles of Rostock [36] RepRap derivative 3-D printers. The RepRap could print all (10) polymer components to; (1) mount the PV modules; (2) mount the battery; and (3) provide mounting and covering the Melzi board [37]. The rendering of the 3-D printable components are shown in Figures 4–6.

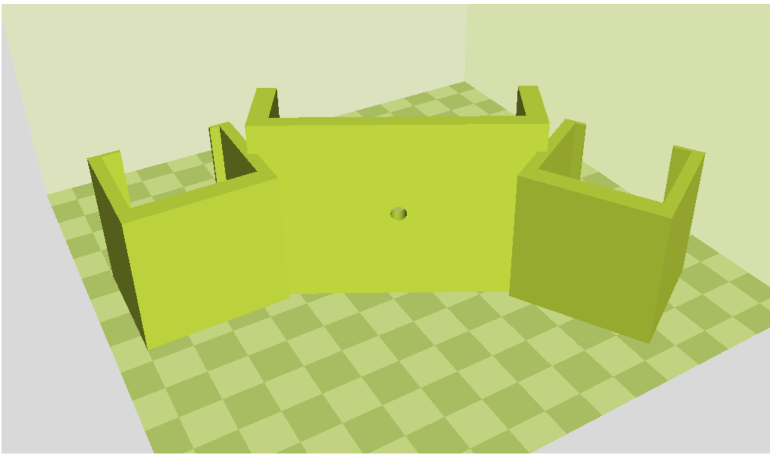

Figure 4. Rendering of OpenSCAD solid model for the solar PV module holders for the MOST delta RepRap PV conversion kit. Two holders are mounted at the bottom and top of each of the three vertical supports of the delta for a total of six holders using wood screws.

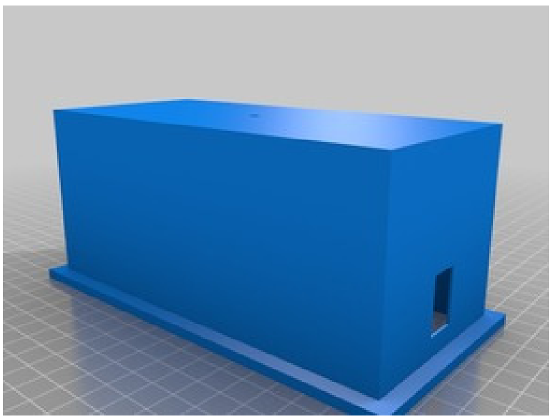

Figure 5. Rendering of OpenSCAD solid model for the battery casing for the MOST delta RepRap PV conversion kit.

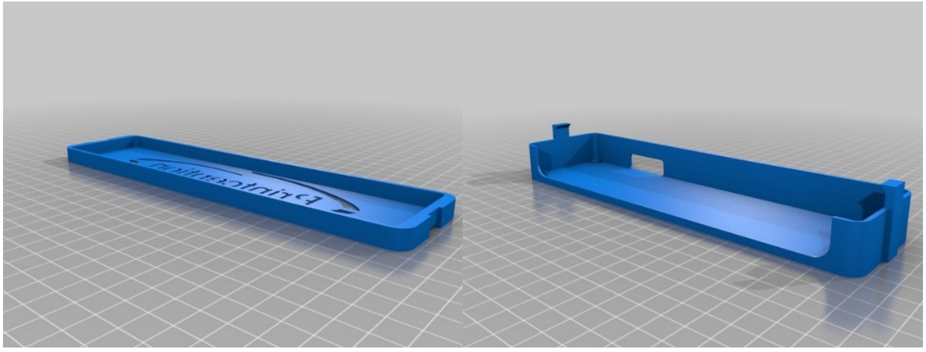

Figure 6. Rendering of OpenSCAD solid model for Melzi board electronics cover.

2.3. Experimental Methods

The solar charging and printing performance were tested and the printing time from full charge in the dark was determined printing different objects, which included a scaled-down size chicken feeder [38]. The chicken feeder is shown in Figure 7.

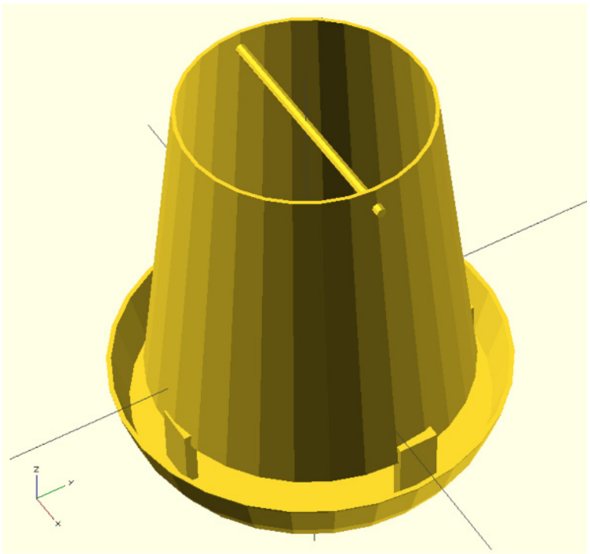

Figure 7. Rendering of OpenSCAD solid model for the chicken feeder.

To measure the change in the battery state of charge (SOC) a coulomb counter was used. The coulomb counter measures the change in SOC by integrating the current that flows in and out of the battery over time. The device used in this work has a voltage acquisition accuracy and a current sampling density of 1%. Coulomb counting is a useful and simple method of measuring a battery's SOC change. However, an issue may arise; errors due to the precision of the measurement can increase over time, since the method is a pure integration [39]. In order to avoid that problem, the Coulomb counter was reset for each experiment. That way, the error is not carried out between experiments and the overall error of each experiment was kept as low as possible, being nearly unnoticeable.

The incident solar flux was measured using a pyranometer located at the Keweenaw Research Center (KRC), Calumet in Michigan. Small differences in the data could be observed due to the seven miles distance between KRC and the Michigan Technological University main campus, where the experiments were performed. A multimeter and a current clamp were used to measure voltage and current, respectively. Measurements were taken every 10 min for experiments one and two. The printer's power requirements varies during its heating calibration. As would be expected, it requires more power when it is heating up and less power when it is cooling down. As the process of calibration is fast, not all those variations appear in the charts, since a calibration can happen in the interval of two measurements. Although it is not possible to get those variations, the measurements do show how the system works over time, exposing how the solar flux affects the voltage and current across the system. For experiments three and four, measurements were taken every 15 min. Those experiments were aimed at measuring the battery SOC change. As the coulomb counter used in this work integrates current over time, its measurements perfectly acquire the SOC change, showing how the battery state of charge will change due to the variations in solar flux and the variations due to the heating calibration of the printer.

The system was tested under five conditions:

1. PV modules charging the battery and driving the 3-D printer.
2. System working under low insolation.
3. Battery powering the 3-D printer (no PV).
4. PV modules charging the battery only (no printing).
5. Battery fully charged and the PV modules power the 3D-printer.

3. Results and Discussion

Figure 8 shows a MOST-delta 3D printer and PV stand-alone power system assembly in transit in a duffel bag. The PV module holders in Figure 4 (in red) are used to secure the solar modules to the 3-D printer frame, the battery casing secures the battery to the top of the printer and the electronics casing protects the Melzi controller board during transit.

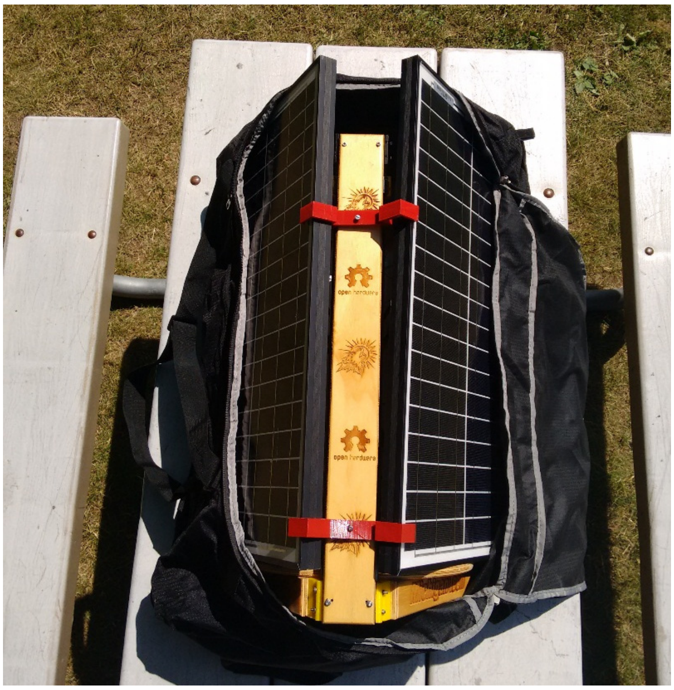

Figure 8. Photograph of the MOST-delta 3D printer and PV stand-alone power system assembly in transit in a duffel bag. For transportation the modules are mounted on all three sides of the delta.

Figure 9 shows the 3-D printer with a PV stand-alone power system deployed for testing on a picnic table. Two of the modules are simply propped up against the picnic table and the third one remained attached to the 3-D printer. The arrangement of PV is up to the operator and the system works with all three unmounted, two mounted, *etc.* In general, at least one module must be removed for easy access to the print bed when operating.

Figure 9. Photograph of the MOST-delta 3D printer and PV stand-alone power system assembly with PV deployed.

The system performed well in the five different tests with the switches' conditions adjusted for each of the above tests as described in Table 1.

Table 1. Summary of switch positions for test conditions.

Switch No. 1	Switch No. 2	Tests Performed
ON	OFF	4
ON	ON	1, 2, and 5
OFF	ON	3

During the experimental tests, the voltage at Buck Converter 2 was kept at 12.2 V. A higher voltage was necessary to account for the losses in the wires. Setting the voltage at 12.2 ensured that the 3-D printer terminal would receive 12 V. Figure 10 shows the current in the system in a day with good solar insolation. The PV panels are supplying the printer and charging the battery. At some point during the experiment (3:43 PM), a drop in current is observed due to clouds passing over the test area. At this particular moment, the panels are not able to produce enough to power the printer. $I_{battery}$, the battery current, is considered to be negative during charging and positive when the battery is discharging. As we can see in the Figure 10 at 3:43 PM, the battery changes from charging to discharging mode, compensating for the drop in current from the PV modules. After an hour of printing, the battery SOC increased by 4.5% and the load was provided with enough power to print. The variation of voltage in the printer's terminals was of less than 1.5%, ensuring that it would provide the required power. I_{panels} and $I_{printer}$ represent the current supplied by the PV modules and the current fed into the printer, respectively.

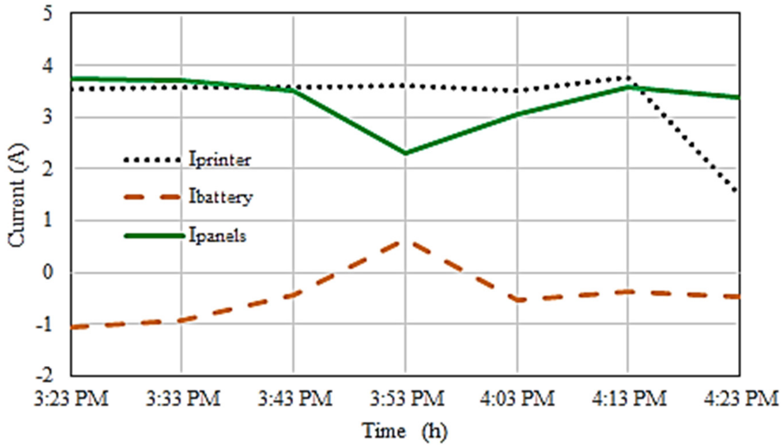

Figure 10. Variation of current across the system during Test 1.

Figure 11 shows the variation of current across the system during the second test, which was performed under low solar insolation. At the start of the test, the PV panels were supplying both the printer and charging the battery at the same time. As solar insolation starts to drop, the battery changed from charging to discharging mode. At the printer's low power peaks, when it is calibrating the extruder temperature, such as at 5:48 h, the battery reverts back to charging mode, using up the excess current provided by the PV panels. As solar insolation continued to drop/decrease, the amount of current fed back into the system network from the battery increased, guaranteeing enough power to the 3-D printer. After 1 h and 27 min of printing, the battery SOC dropped by 3.5%. The voltage in the printer's terminals reached a maximum of 12.14 V, which constitutes a variation of less than 1.5% from the targeted 12 V. It should be noted small differences in total are due to measurement time delays (*i.e.*, such as at 6:28).

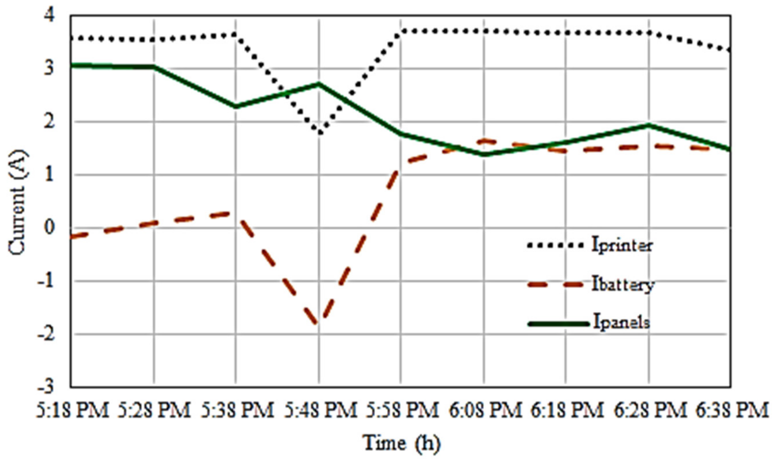

Figure 11. Variation of current across the system network during Test 2.

The change in the battery SOC when printing on the battery alone is shown in Figure 12. The battery was able to supply enough power to the system for 7 h and 18 min, time in which multiple objects were printed. The battery state of charge drops almost linearly during the printing. The 3-D printer voltage reached a maximum of 12.11 V and a minimum of 11.85 V, the total variation is less than 2.5%. Although this is a small variation, it is still larger than the variations observed in the previous experiments. This is because the battery is almost fully discharged. The terminal voltage is much lower than the 14.4 V nominal value. The losses in the second buck converter force the output to be less than 12 V, though its duty cycle was at maximum. Moreover, the battery is suffering from concentration polarization [40], thus the battery terminal voltage drops rapidly in the low SOC region, causing a higher variation in the output.

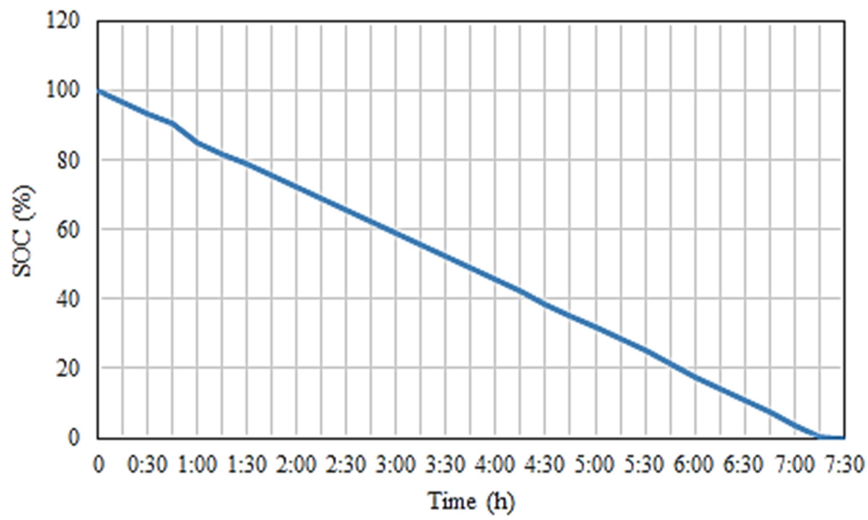

Figure 12. Change in the battery SOC during discharge of Test 3.

Figure 13 shows the change in the battery SOC when PV panels are charging the battery only. Though the battery was fully discharged, the battery protection circuit mounted on it prevents discharging after a certain depth of discharge (DOD). Moreover, these protection circuitry also enforces a proper constant current, constant voltage (CC-CV) charging profile [41] according to the lithium ion technology. The CC-CV charging has three phases, a low CC region, a CC region with at least 1 C and a CV region. The protection circuit of this battery limits the initial charging current. Thus, the SOC increased by 9.5% in 45 min. Moreover, the test was performed under low insolation conditions; therefore, a much higher SOC would be anticipated for the same period if the test were performed cycling the battery to a higher DOD and under higher solar insolation conditions. In this test the Switch 2 was closed and, as expected, there was no voltage at the 3-D printer.

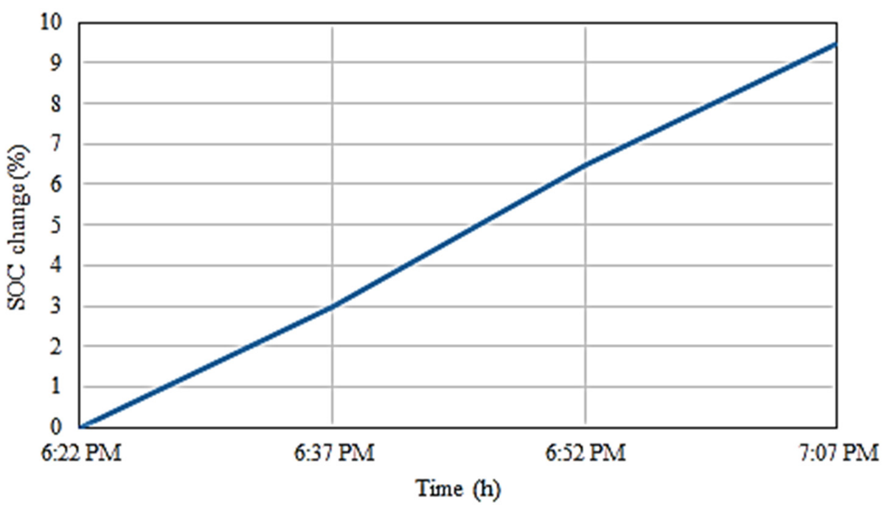

Figure 13. Change in the battery SOC during charging for Test 4.

During the last experiment, with the battery fully charged and the PV panels providing the supply, the system worked as expected. The battery provided little or no power to the 3-D printer for the entire 30 min of printing, and the battery SOC remained almost constant. The system worked well in all experiments, with the printer's maximum voltage variation being of less than 2.5%. The output of Buck Converter 1, set to be 16.8 V, varied more. This happened because Buck Converter 1 is directly connected to the battery terminals whose voltage depends on its state of charge and whether it is being charged or discharged. This, however, does not affect the reliability of the system as these variations are suppressed by the second buck converter. It should be noted that, when the printer was autonomously powered by the battery, uninterrupted print periods greater than seven hours are possible, meaning that multiple objects can still be printed well after loss of the PV modules' power. In addition with Franklin firmware [42], true power failure recovery is possible during a print. The results show that the new design validated here is a considerable improvement over the mobile solar-powered 3-D printers demonstrated in the past (with initial total cost of US$2500) [28], which required two 220 W modules and four 120 Ah batteries. Here 1/6 the battery storage and 1/5 the PV power resulted in a print time of nearly a working day without any solar flux. Furthermore, the FoldaRap 3-D printer used in the past can only print smaller components (140 mm × 140 mm × 155 mm) [28,43] compared to those printed on the MOST-Delta printer (250 mm diameter, 240 mm high cylinder) [44]. The cost of the designed system is approximately $630 plus the $400 for the delta RepRap components. The former price is expected to decline since the PV were purchased at $2.20/W and can be found at a much lower price on the international market. Moreover, as more people start to work on it, improvements will make it possible to lower the price of the system further.

As the results have shown, the designed system can be used in any off-grid community with access to sunlight for distributed manufacturing of polymer products with reasonable tensile strengths [45–49]. Families can print customized items for personal use, their community, or for income generation [50]. For example, communities can print critical products such as eye glasses [19]. When made locally, they will be affordable to many resulting in reduction of vision problems in the developing world and promoting access to education [19]. They can also print parts to build more RepRap printers, or/and replacement parts for existing machines. Armed with the printers, these communities will be able to innovate; they will be able to design and make new tools to satisfy their own needs and the needs of neighboring communities. The continued development of the recyclebot [51], a device that takes shredded waste plastic and extrudes it into usable 3-D printer filament, and similar systems [52] presents an alternative to centralized recycling and an opportunity to add value to recycled plastic. Current recyclebot technology allows waste pickers to transport their low density recycled material (e.g., HDPE [53]) to a local recyclebot station to be turned into high-density, high-value 3-D printer filament, thus enabling them to make more money for their labor and to produce low-cost material for distributed manufacturing. Further, the concept of fair trade filament, which includes minimum pricing and regulated work hours, would benefit waste pickers and their communities by enabling upward economic mobility and increased development opportunities [54]. Additional work is needed at looking at a closed loop integrated recycling system for 3-D printing to reach a sustainable state [52]. Future work is also needed to develop a similar power system to the one demonstrated here to power the recyclebots technology to further reduce the costs of the ecosystem. In addition, the RepRap presented here would benefit from more advanced features. such as defect detection during printing [55]. Finally, 3-D-printable PV modules and low-cost, low-power laptops are desirable for this application.

4. Conclusions

This paper proposed a low-cost, simple, and mobile solar-powered 3-D printer system. The system consist of a PV stand-alone power/battery charging system integrated to a MOST-delta 3D printer. 3D printed conversion parts are used to secure the panels to the printer frame, as well as to protect vulnerable printer components, such as the Melzi controller board, Li-Ion battery pack and the power supply circuitry during transit. The whole assembly easily fits into a 36 inch (91 cm) drop-bottom wheeled duffel for transport to a location of interest. The designed system was subjected to performance tests under varying levels of insolation and the results showed that the system performed as predicted.

The design validated here is a considerable improvement over mobile solar-powered 3-D printers demonstrated in the past. The innovations presented in this project are of great significance in general to all 3-D printing operators who now have the choice of transporting their mobile systems wherever they desire without the limitation of grid electricity. This also has far reaching implications for the adoption of 3-D printing technology in off-the-grid rural communities to enable distributed manufacturing. The solar powered 3-D printer enables communities to set-up backyard factories with the capacity to locally fabricate customized products of significant value to these and surrounding communities. 3-D printers, powered by optimized and affordable mobile PV solar systems, have a great potential to reduce poverty through employment creation as well as ensuring a constant supply of scarce products. including replacement parts.

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Author Contributions: J.G. and D.F. performed the experiments, helped with the data analysis and took the lead on the writing, K.Y.K. and L.G. perfomed the simulations and helped guide the design and J.M.P. formulated the project and assisted on the analysis. All authors co-wrote and edited the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Table A1. Bill of materials and material specification of the components and accessories.

Component	Quantities	Source	Cost (US$)
DROK®12 A/100 W 5–40 V to 1.2–36 V DC Buck Volt Converter	2	amazon.com	21.98
Polymer Li-Ion Rechargeable Battery Pack: 14.8 V 20 Ah (296 Wh) — UN38.3 Passed	1	batteryspace.com	260.00
ALEKO®30W Monocrystalline Solar Panel	3	amazon.com	197.97
High Sierra AT2 36" (91 cm) drop bottom wheeled duffel	1	amazon.com	139.99
Bolt with nuts			
5 Pcs SPST On/Off Momentary Off Rocker Switch AC 250 V/6 A 125 V/10 A	2	amazon.com	4.44
Total			625.70

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