Energy for Sustainable Development 36 (2017) 1–5

Contents lists available at ScienceDirect

Energy for Sustainable Development

3-D printing solar photovoltaic racking in developing world

Ben Wittbrodt [a], Joshua M. Pearce [a,b,*]

[a] Department of Materials Science & Engineering, Michigan Technological University, United States
[b] Department of Electrical & Computer Engineering, Michigan Technological University, United States

ARTICLE INFO

Article history:
Received 13 October 2014
Accepted 10 August 2016
Available online xxxx

Keywords:
Developing world
3-D printing
Sustainable development
Open-source
Photovoltaic
Racking

ABSTRACT

The purpose of this paper is to provide a technical and economic evaluation of the value of the RepRap as an entry-level 3-D printer in the developing world and provide a cost effective solar photovoltaic (PV) racking solution to better serve the developing world and aid in the acceleration of their economic and socioeconomic growth. A customizable open-source PV racking concept is designed, prototyped for three types of modules, constructed into systems, and outdoor tested under extreme conditions for one year. An economic analysis is provided along with a technical evaluation of the system, which found the proposed racking system can be successfully printed with RepRap 3-D printers and saves between 85% and 92% from commercially available alternatives depending on the plastic used for printing. In addition, the plastic parts proved able to withstand some of the harshest outdoor conditions and due to the free and open-source nature of the designs, it allows the system to be adapted to custom applications in any region in the world more easily than any commercial alternatives. The results indicate that the 3-D printable X-wire solar photovoltiac racking system has the potential to aid in the acceleration of solar deployment in the developing world by providing a low cost PV racking solution.

Introduction

Various additive manufacturing technologies has been used in industry to prototype new products for decades (Yan and Gu, 1996; Pham and Gault, 1998;Kruth et al., 1998; Leu et al., 2012; Mitsuishi et al., 2013), but until the introduction of the RepRap project (Self-Replicating Rapid Prototyper) brought entry level devices s to the market, 3-D printing was not a realistic purchase for most households. The RepRap project aims to provide a cost effective 3-D printer based on open-source software and libre hardware that encourages collaboration between many people throughout the world (Jones et al., 2011). This allows a greater number of people to both contribute to and benefit from the project simultaneously (Jones et al., 2011). Currently, an entry-level RepRap can be built near, or below, $500 in parts (Wittbrodt et al., 2013) with costs continuing to decline as the popularity of 3-D printing rises (Wohlers Associates, 2013). These price declines are moving the technology from an industry specific technology to one that could be used in the developing world (Pearce et al., 2010; Campbell et al., 2011; Lipson and Kurman, 2013; Tanenbaum et al., 2013).

Current estimates of the world's poor show that the issue of poverty is a much greater threat than initially thought and it is imperative that efforts are made to increase the standard of living (Chen and Ravallion, 2008). Today it is estimated that 2.6 billion without any sanitation (Dugger, 2006) and for cooking, 2.5 billion people are forced to use biomass, fuel wood, charcoal, or animal dung as energy in order to eat (Shah, 2013). In addition, over 2 billion people live without access to electricity (Reiche et al., 2000), For example, with only 0.2% of rural areas in Zimbabwe having access to the grid the cost of extending the grid hinder the growth and development of the country (Drennen et al., 1996). As efforts are made to develop other areas of the world, with electrification for example, it is important to utilize sustainable development practices to reduce the future impact of a greater number of developing areas (Drennen et al., 1996).

Access to electricity has been shown to accelerate development (Reiche et al., 2000) and being able to use basic electric appliances (e.g. lighting, water pumps, cell phones) can springboard development with improvements to education, sanitation, nutrition, and industry (Reiche et al., 2000; Kanagawa and Nakata, 2008). 3-D printers can be one of the electrical appliances and further their ability to develop and produce needed items and replace broken components of a large variety of systems with specialized parts that would otherwise be unavailable (Pearce et al., 2010). One technology that has been shown to be particularly useful in sustainable electrification of rural developing communities is solar photovoltaic (PV) technology (Acker and Kammen, 1996; Pearce, 2002).

Although PV prices have dropped considerably (Branker et al., 2011), one of the remaining fixed costs that have not declined is the relative cost of the balance of systems (BOS) related to the total cost of a PV array (Fthenakis and Alsema, 2006). The BOS includes racking, wiring and electronics necessary to complete a PV system. Hence, for PV to be competitive with traditional energy generation methods, more work must be done to reduce manufacturing PV costs and BOS costs (Lewis,

* Corresponding author at: 601 M&M Building, 1400 Townsend Drive, Houghton, MI 49931-1295, United States.
E-mail address: pearce@mtu.edu (J.M. Pearce).

http://dx.doi.org/10.1016/j.esd.2016.08.001
0973-0826/

2007). One way presented to decrease the BOS costs is utilizing low-cost distributed manufacturing with a RepRap 3-D printer for small-scale mobile PV arrays (Wittbrodt et al., 2015).

This study evaluates the technical and economic viability of distributed manufacturing of PV racking in the developing world using entry-level RepRap 3-D printers. A customizable open-source PV racking concept is designed, prototyped for three types of modules, constructed into a system, and outdoor tested under extreme conditions for one year. The technical viability of using commercial 3-D printer filament and recycled plastic waste is determined for outdoor use in this application. Finally, a detailed economic analysis is performed.

Methods and materials

A ground-mounted PV racking system was designed in OpenSCAD, 2014.03 (OpenSCAD, 2014) a free and open-source solid modeling program, using parametric variables that automatically manipulate the entire part to enable simple modifications without the need for knowledge in 3-D modeling. These OpenSCAD code generates 12 different STL files for all the potential geometries of an infinite scaled array. The STL files were sliced in the open-source Cura (Ultimaker, 2014) before printing with solid 100% infill on a MOST Prusa RepRap (MOST, 2014) using Repetier-Host (Repetier, 2014) to drive the printer. Once the parts were completed threaded steel rods were inserted into the parts for added strength and support and tightened down with nuts. Steel wire was threaded through the mounting brackets in a X shaped pattern under the modules to tensions the modules together giving name to the system of X-wire. The detailed bill of materials (BOM) needed to assemble the X-wire system can be found in Table 1, including the cost of the tools.

The OpenSCAD design includes parametric variables that allow quick and easy changes to the module tilt angle and size of the module as shown in Fig. 1. Pictured are two brackets setup for 10° of tilt and 20° of tilt showing the difference in the cup angle and height. Each bracket is paired with an extension bar of appropriate height as well. If the user decides to expand the PV array in the future additional parts can be printed out to fit the new modules and simply added to the existing array. It is also possible to use this system on every framed PV module whether it be a smaller mobile module (GoalZero, 2014), or large full-scale modules used here (Sharp, 2014).

Once the parts were printed and fit for the modules the racking system was assembled and placed outside and the brackets were tied down with more wire and tent stakes to ensure the modules did not lift off the ground due to wind loads.

The brackets were subjected to outdoor weather conditions for one year to validate the resilience of the parts. The parts were massed and the printing time was monitored to evaluate the cost of production. A 10° tilt system was used for analysis but a sample bracket at 20° was printed to prove the customizability of the design (as shown in Fig. 1). Following the printing and assembly a detailed economic analysis was performed comparing the Unirac RM (Unirac, 2014) racking system to the X-wire system when printed in commercially available polylactic acid (PLA) and recycled high density polyethylene (HDPE) filament. The Unirac system is advertised as one of the easiest and quickest racking systems to setup. While it is a roof mounted system it can be ballasted on the ground or easily staked into the ground to properly secure the RM system. Additionally the outdoor material behavior was examined theoretically using available literature on UV degradation and resilience of common 3-D printable materials.

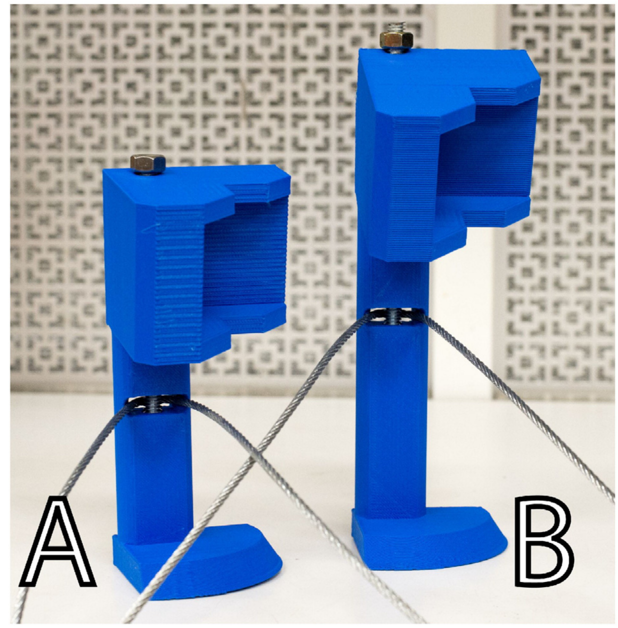

Fig. 1. a) 10° and b) 20° tilt angle x-wire 3-D printed brackets fully assembled. Those shown here are for the back corners of the array. The cups in the upper portion of the brackets hold the corners of the PV modules.

Results

A 1 kW PV array consisting of four 250 W PV modules, was successfully constructed, as shown in Fig. 2, using the X-wire system. The array was deployed outside for the winter of 2013/2014 in the upper peninsula of Michigan and subjected to harsh temperatures and heavy snow loads as measured by the Keweenaw Research Center (KRC) (2014), where the system was setup. Once the snow fell the temperature at the level of the racking was between 19 °F [−7.22 °C] and 24 °F [−4.44 °C] for the duration of winter and had a maximum depth of snow of 39 in. [0.99 m]. With a ground snow load of 100 lb/ft^2 [488.2 kg/m^2] (Energy, 2010) an estimate of the snow load on the 10° tilted modules is 84 lb/ft^2 [410.12 kg/m^2] (Ochshorn, 2009). All 100% fill parts remained intact.

When compared to a commercial racking system the X-wire system is significantly less expensive with a savings of 83% (with commercial PLA) to 92% (with recycled HDPE) as shown in Table 2, which does not include import duties. With the X-wire system the largest individual cost is the printed plastic with 1.5 kg/kW used at $33 per kg. Using a new technology, the Recyclebot (Baechler et al., 2013), which converts

Table 1
BOM of the 1 kW assembled X-wire system.

Bill of materials							
Type	Item name	Source	Item No.	Quantity	Unit	$/Qty.	Price per item
Metal	M8 rod	McMaster	90024A080	1.25	Meter	$8.31	$10.39
	Steel wire	McMaster	8908T66	11.88	Meter	$2.76	$32.74
	Hex nuts	McMaster	91828A410	18	Count	$0.20	$3.60
Plastic	PLA filament	Prototype supply	3 mm silver	1.5	Kg	$36.00	$54.00
Tools	13 mm wrench	McMaster	71405A38	1	Count	$10.98	$10.98