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# Solar Energy-Harvesting E-Textiles to Power Wearable Devices †

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**Abstract:** This work presents an innovative solar energy harvesting fabric and demonstrates its suitability for powering wearable and mobile devices. A large solar energy harvesting fabric containing 200 miniature solar cells has been shown to charge a 110 mF textile supercapacitor bank within 37 s. A series of solar energy harvesting fabrics with different design features, such as using red or black fibres, were tested and compared to a commercially available flexible solar panel outside under direct sunlight. The results showed that the solar energy harvesting fabrics had power densities that were favorable when compared to the commercially available solar cell.

**Keywords:** electronic textiles; E-textiles; photovoltaic; solar; energy harvesting

## 1. Introduction

The requirement to power electronic textiles (E-textiles) has been a major contributor to their poor commercial adoption. In this work a novel solar energy-harvesting textile that is both aesthetically pleasing and mechanically robust is presented. The textile solar panel was created by weaving textile yarns with embedded miniature solar cells (solar-E-yarns), fabricated using the E-yarn technology [1]. The solar-E-yarns and resultant fabrics had the hand feel (soft, conformable and breathable) and the appearance of regular textiles. These textiles were also wash durable, making them superior to the textile-based solar energy harvesting solutions reported in the literature [2,3].

The solar-E-yarns were fabricated by soldering miniature solar cells onto two fine multi-strand copper wires before individually encapsulating them inside of clear resin micro-pods. The encapsulated cells and the copper wire interconnections were then covered by a fibrous textile sheath, comprising of packing fibres and a tubular knitted structure. The fibrous sheath could take any colour, depending on the required colour of the solar-E-yarn and resultant fabrics. This offered a major advantage over other proposed solar E-textiles, where the photovoltaic component was visible on the surface affecting the aesthetics of the resultant textile in many cases. The performance of solar-E-yarns and resultant fabrics could be further enhanced by impregnating the photoactive side of the yarns with a clear resin.

This work presents a series of solar energy harvesting fabrics and demonstrates their utility for powering devices. The capability of a solar energy harvesting fabric containing 200 solar cells to charge a 110 mF (3.2 V) textile supercapacitor bank was evaluated. Further, four solar energy-harvesting fabrics with different material combinations (white fibres, red fibres, black fibres, and white fibres with resin impregnation) were tested outside and compared to a commercially available flexible solar cell.

## 2. Materials and Methods

### *2.1. Solar Energy Harvesting Fabric Construction*

The solar-E-yarns were created by soldering ten miniature crystalline silicon solar cells (1.5 mm × 3.0 mm × 0.2 mm; Solar Capture Technologies, Blyth, UK), in parallel, onto two multi-strand copper wires (seven strand, single strand diameter = 50 μm, electrical resistance = 1.35 Ω/cm; Knight Wire, Potters Bar, UK) using a reflow soldering technique (PDR IR-E3 Rework System, PDR, London, UK). The solar cells were individually encapsulated along with a supporting yarn (Vectran™, Kuraray America Inc., Houston, TX, USA) within an optically transparent polymer resin micro-pod (9001-E-V3.5, Dymax Corporation, Torrington, CT, USA). Subsequently the ensemble was covered with four packing fibres and a polyester, knitted, tubular sheath (created using a RIUS MC-Knit braider; RIUS, Barcelona, Spain). The completed solar-E-yarns (Figure 1a) were woven into fabrics using a four shaft-weaving loom (Harris Looms, Ashford, UK). The white polyester warp yarns were threaded to achieve a four by one shedding pattern (a basket weave). The woven fabric was created by inserted the solar-E-yarns in the weft direction. The solar-E-yarns were inserted in such a manner that the photoactive side was fully exposed on the front surface of the fabric. Five fabrics were presented in this work, a textile containing 200 solar cells (Figure 1b), and four fabrics, each containing 50 solar cells; one where white polyester fibres were used to create the fibrous sheath of the solar-E-yarns, one where red polyester fibres were used, one black polyester fibres were used, and one where the white polyester fibres where impregnated with resin (9001-E-V3.5) at the micro-pod to improve the optical properties (Figure 1c).

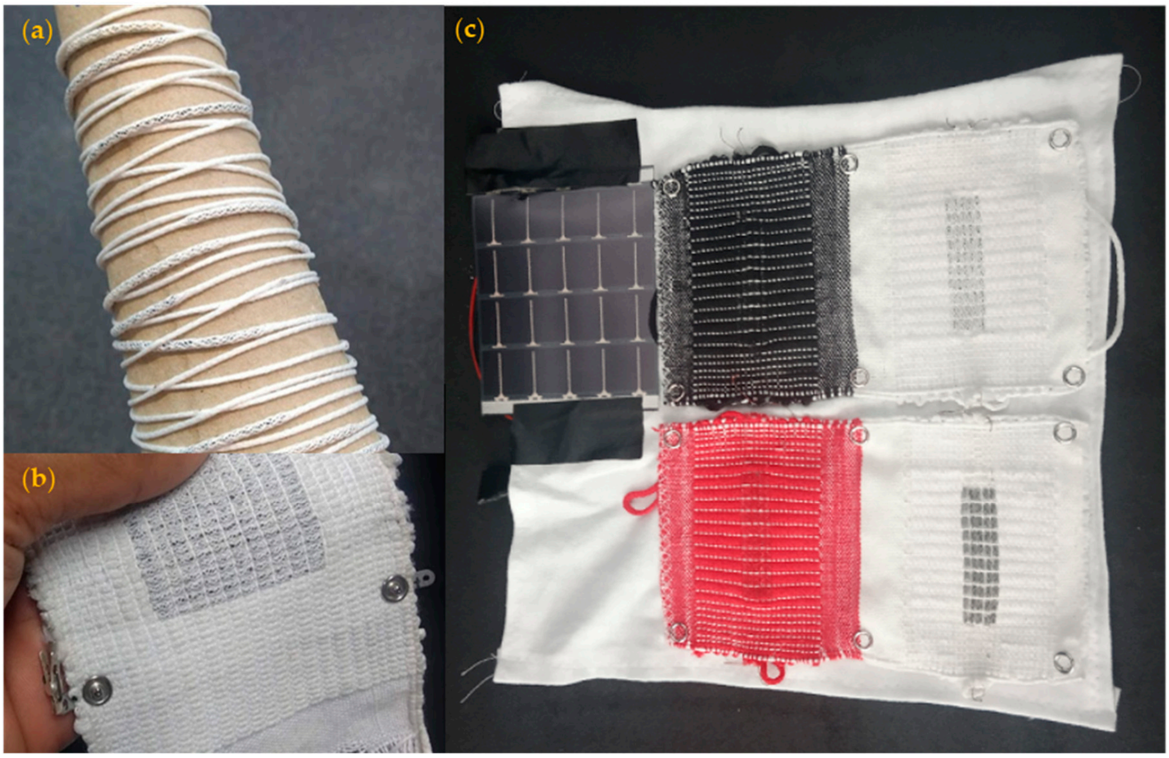


**Figure 1.** (**a**) Solar-E-yarns prepared with ten individually soldered and encapsulated solar cells. (**b**) Solar energy-harvesting fabric prepared with 200 solar cells. (**c**) Solar energy-harvesting fabrics (each containing 50 solar cells) and a commercially available flexible solar cell.

### *2.2. Charging Performance*

The large solar energy-harvesting fabric (the fabric that contained 200 solar cells) was used to charge a 110 mF (3.2 V) textile supercapacitor bank. The supercapacitor bank was created by embedding ten CPH3225A supercapacitors (11 mF, 3.3 V, 3.2 × 2.5 × 0.9 mm; Seiko Instruments Inc., Chiba, Japan) within a textile yarn in a similar fashion to the solar-E-yarns described above. The textile supercapacitor bank was charged by the large solar energy harvesting fabric using a solar simulator as the light source (Oriel LSH-7320 ABA Solar Simulator, Newport Corporation, Irvine, CA, USA). The textile supercapacitor bank was connected to the solar fabric demonstrator and charging was performed under 100%, 75%, 50%, 25% and 10% of one sun intensity. The charging voltage was monitored using a multi-meter (Model 34410 A 6 ½, Agilent Technologies LDA UK Limited, Stockport, UK).

### *2.3. Field Test Procedure*

A field test under natural sunlight to evaluate the comparative behaviour of different solar energy harvesting fabrics was conducted. An autonomous mobile data acquisition device (DAQ) was built using a Teensy 3.5 development board as its base (PJRC, Sherwood, OR, USA). The DAQ was designed to record the voltage across fixed 1 kΩ load resistors connected to the four small solar energy harvesting fabrics (the fabrics that each contained 50 solar cells) and a commercially available flexible solar module (MPT4.8-75, flexible solar module with 0.24 W peak power; PowerFilm Solar Inc., Ames, IA, USA). The solar fabrics were positioned onto a T-shirt with the individual solar-E-yarns of the solar fabrics positioned vertically, when worn. The T-shirt was dressed onto a mannequin and placed outdoors, with the solar modules facing North, on a sunny day (17 September 2019 from 1.00 P.M. and 2.30 P.M., in Nottingham, UK).

## 3. Results

### *3.1. Charging Performance of the Solar Energy-Harvesting Fabric*

The charging performance of the solar energy-harvesting textile using the textile supercapacitor bank under five lighting conditions is shown in Figure 2.

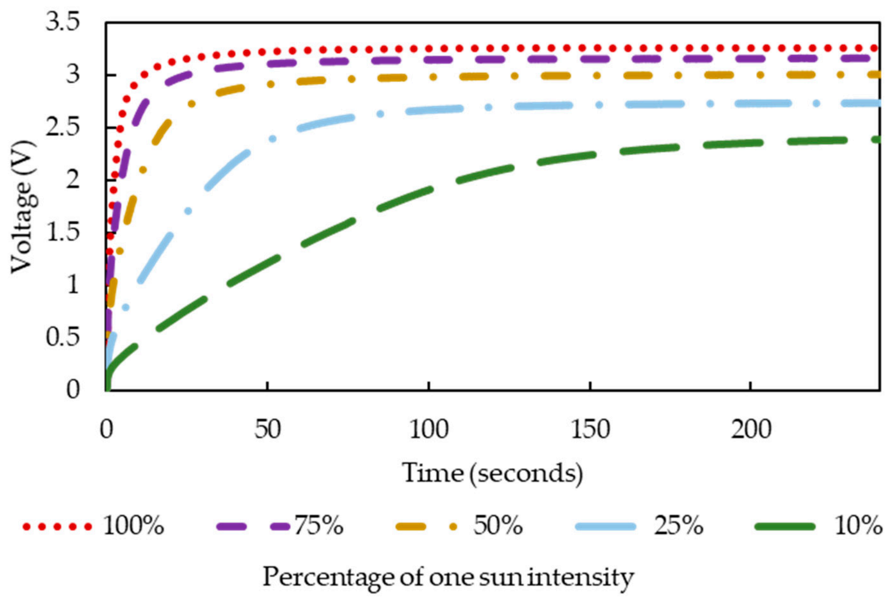


**Figure 2.** Charging a textile supercapacitor bank using the solar energy harvesting fabric demonstrator under different lighting conditions. The discontinuous lines are shown to distinguish between datasets only.

Figure 2 clearly shows that the solar energy harvesting fabric could quickly charge a textile energy storage device, providing a fully textile energy solution. At one sun intensity the 110 mF supercapacitor bank was charged to 3.2 V in 37 s; this corresponds to 0.56 J of energy.

*3.2. Solar Energy Harvesting-Fabric Field Tests*

The power densities calculated for the solar energy harvesting fabrics and commercially available flexible solar panel are shown in Figure 3.

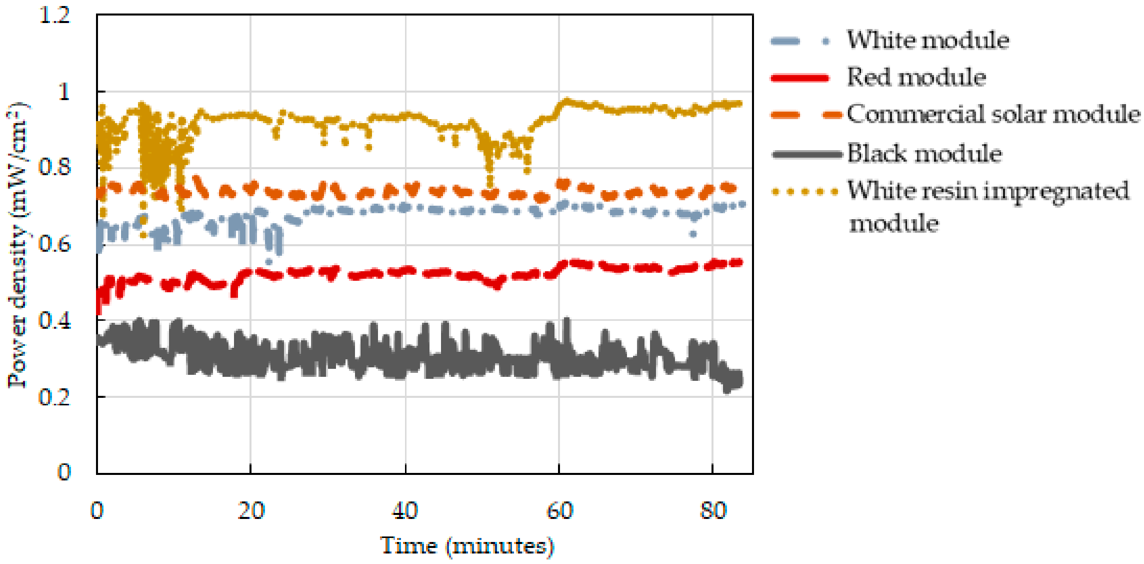


**Figure 3.** Power densities for the five different solar modules tested (four solar energy harvesting fabrics and one flexible commercial solar cell) collected over 85 min. Data was collected at a sampling rate of 1 Hz; the discontinuous lines are shown to distinguish between datasets only.

The results showed that the white solar energy harvesting fabric and the commercial available flexible solar panel had comparable power densities. The enhancement in power density due to impregnating the upper fibres of the solar-E-yarns with resin showed power densities that were 35.3% higher than for the white solar energy harvesting fabric and 24.3% higher than for the flexible solar panel. The black and red solar energy harvesting fabrics generated power densities lower than the white solar energy harvesting fabric (54.4% and 23.5% lower respectively). The results of the field test confirm that solar energy harvesting fabrics were suitable for generating power under natural sun light.

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

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