



A SELF POWERED BACKPACK FOR WEARABLE SYSTEMS

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ABSTRACT

A backpack that powers itself is proposed for hikers, students, travelers and other users who stay outdoors for extended periods and need to recharge portable devices. Its outer face carries a polycrystalline photovoltaic cell of 88 cm², and a rubber bladder holding drinking water sits behind the cell. Four prototypes are prepared: the cell is used alone in prototype 1, whereas in prototypes 2, 3 and 4 the bladder holds tap water, iced water and hot water, respectively. Load sweeps from 47 Ω to 10 M Ω are recorded for each prototype in direct sunlight, in outdoor shade and indoors. Prototypes 1 and 2 give the best result, 1223.3 mW in direct sunlight with a 73 Ω load, which is 13.9 mW/cm² and 72% of the 1.7 W rating. Prototypes 3 and 4 reach 905.4 mW and 634.0 mW, respectively. The maximum power point current indicates that the cell receives less light in both cases, and that heating or cooling of the cell cannot account for the losses alone. Outdoors the optimal load lies in the tens of ohms, whereas indoors it lies in the tens of kilohms. Moreover, a 2400 mAh battery pack is charged from prototype 1 through BQ25570 and LM2596 power management circuits. With the LM2596 the pack voltage reaches 2.4 V after 5 min, against 11 min with the BQ25570, whereas the BQ25570 starts from 600 mV and is better matched to indoor light.



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1. Introduction

Phones, laptops, loudspeakers and fans all run on electrical energy, most of which is still generated from coal, oil and other fossil fuels. Fossil reserves are finite, and their combustion emits carbon dioxide that warms the planet. Solar energy is abundant and widespread, and its potential exceeds the global electricity demand.

Over recent years, wearable electronics have progressed rapidly. Such devices are increasingly personalized and now support daily activities in healthcare, gaming, sport and education [1]. Furthermore, developments in flexible electronics and low power circuit design have produced wearable devices with considerable capability.

A wearable device needs an uninterrupted power supply, whereas its battery offers only a finite operating life. Harvesting ambient energy can supplement the battery and prolong the service life of the device [1].

Devices that sustain themselves on energy drawn from their surroundings offer a practical route to powering wearable systems. Portable and wearable devices can draw on mechanical [2], thermal [3], chemical and solar [4] energy, each with its own characteristics. Contact followed by separation of 2 dissimilar materials produces triboelectric charge. A piezoelectric material generates charge when it is mechanically strained, whereas an electromagnetic harvester produces power from a conductor moving relative to a magnetic field. All 3 mechanisms turn mechanical work into

electricity, and harvesters based on them are well matched to the motion of the human body. Similarly, biofuel cells rely on enzymes or microbes to catalyze the conversion of chemical energy to electricity, and body fluids offer an abundant supply of the required biochemical fuel. Moreover, the body holds a steady temperature that differs from its surroundings, so a thermoelectric generator can turn body heat into electrical power. Solar energy is clean, renewable and particularly effective for wearable electronics, and combining it with other sources in a hybrid harvester raises the available power and widens the range of devices supplied. Solar powered backpacks follow this approach and keep personal electronics charged on treks, rides and runs.

Progress in flexible electronics and sensing has opened several fields of application, wearable healthcare among them. Plastic films of polyimide or conductive transparent polyester improve comfort, whereas the short battery life of the devices remains a barrier, especially in biomedical use.

Harvesting energy addresses the short operating life of wearable devices, whereas the size, weight and cost of the harvester limit how far this remedy can be applied.

A bracelet for the long term monitoring of patients and elderly people is reported by Jokic and Magno [5], with its complete circuit placed on a polyamide film and supplied by thin film photovoltaic cells designed for up to 90% conversion efficiency. Outdoors one cell yields 16 mW, against 0.21 mW under indoor light, and the energy supports regular blood oxygen readings transmitted by Bluetooth.

The solar jacket of Khan and Khan [4] supplies a body monitoring unit that reports physiological readings every 3 min and issues emergency alerts. Its 10 flexible cells, each 146 mm $\times$ 167.5 mm, sit in clear pockets sewn onto the garment, and a tracking stage improves charging in dim light. A peak of 1282.57 mW is recorded at 780 W/m², equal to 41000 lux. Wu et al. [6] track the optimum operating point of a flexible cell with an analog circuit that senses current only, and the 66.5% overall efficiency is sufficient for a pulse sensor that reports over Bluetooth Low Energy (BLE). Sensor networks spread over the wearer face 2 further constraints, as rigid sensors conform poorly to the body and batteries cap the operating lifetime.

Toh et al. [7] place an ultra low power management circuit on a flexible board, where it charges a supercapacitor from a solar cell while consuming 32.86 μ W itself. The resulting battery free node reports skin temperature to a base station, and at a bend of 30° the harvester gives 56 μ W, which keeps the node running for over 15 hours. Kartsch et al. [8] classify 5 hand gestures from muscle signals with 94.02% accuracy on a band built on a flexible circuit strip, aimed at rehabilitation after stroke or neural trauma and at human machine interfaces. On one 200 mAh cell the band lasts for over 500 hours, and with its solar cell attached the band works without interruption.

Satharasinghe et al. [9] weave small crystalline silicon cells, linked with thin copper wire, into textile yarn, so the cloth still bends, drapes and breathes. After 15 wash cycles approximately 90% of the original output remains, and 200 cells spread over 44.5 mm $\times$ 45.5 mm deliver approximately 2.15 mW/cm² in full sun, adequate for a basic phone.

Tran and Chung [10] attach a 19 cm $\times$ 4 cm flexible photovoltaic (FPV) panel to a BLE body sensor node. A boost stage covers weak indoor light, accepting 0.65 V to 3.0 V and holding 3.3 V at its output with approximately 95% efficiency, whereas a fuzzy logic tracker covers strong outdoor light, where the panel gives up to 500 mW. Even at 2.9 mW/cm², the node lasts up to 950% longer.

On a forearm sleeve studied by Kim et al. [11], the orientation of the cell toward the light influences voltage and power more than its curvature around the arm. Of the tested layouts, 5 narrow cells perform best after boost conversion and reach 94 mW outdoors, so a smaller battery can be used safely.

Sandhu et al. [12] note that kinetic harvesters rarely supply enough energy for real time activity recognition in wearable Internet of Things (IoT) devices used for health tracking and navigation. In the SolAR system, solar cells serve both as the supply and as the activity sensor, and the harvested energy covers the full recognition process. A trial with 21 volunteers yields more energy and better recognition accuracy than kinetic designs, with no external supply.

Backpacks have also been fitted with solar harvesters. Taverne et al. [13] designed a backpack that charges portable devices from solar energy. Selim et al. [14] mounted a 6 cm $\times$ 6 cm solar module on a backpack and recorded a peak of 140 mW into a 100 Ω load and 55 mW into a power bank. In both studies the photovoltaic cell is treated as a charger and tested at one load or with a power bank connected directly. The thermal conditions behind the cell, the optimal load under different illumination and the selection of a power management circuit are left unexamined.

The present work places a photovoltaic harvester on the outer face of a backpack with a rubber water bladder behind the cell. Besides holding drinking water, the bladder allows the rear surface temperature of the cell to be changed while

all other conditions stay the same. The work contributes in 3 ways. First, the cell is tested over loads from $47\ \Omega$ to $10\ \text{M}\Omega$ in direct sunlight, in shade and indoors, which identifies the optimal load for each case and the extent of its shift between outdoor and indoor operation. Second, the bladder is tested at 3 water temperatures and its effect is split into a voltage component and a current component, which reveals whether it cools the cell or blocks part of the incident light. Third, a boost type and a buck type power management circuit are tested on the same harvester, and the input range of each is compared with the measured optimal loads.

1.1 Objectives

The present work pursues 4 objectives.

1. To build a photovoltaic harvester integrated in a backpack in 4 configurations, identical except for the thermal condition behind the cell, so that the role of the rear surface temperature can be isolated.
2. To test each configuration across loads from $47\ \Omega$ to $10\ \text{M}\Omega$ under 3 illumination conditions, namely direct sunlight, outdoor shade and indoor artificial light, and to identify the optimal load for each.
3. To establish whether water at a set temperature held against the rear surface of the cell raises or lowers the delivered power compared with the unconditioned cell.
4. To evaluate the BQ25570 boost converter against the LM2596 buck converter in charging a 2400 mAh battery pack, in input voltage range and in conversion loss, and to identify the suitable circuit for each illumination condition.

2. Development of the Self Powered Backpack Prototypes

Figure 1 depicts the developed backpack, which centers on a photovoltaic energy harvester. One polycrystalline cell is placed in an outer pocket, as shown in figure 1 (a), and a rubber water bladder is placed against its back inside the bag, as shown in figure 1 (b). The bladder is used for drinking water and, once filled at a selected temperature, for setting the temperature at the back of the cell while the remaining conditions are held fixed.

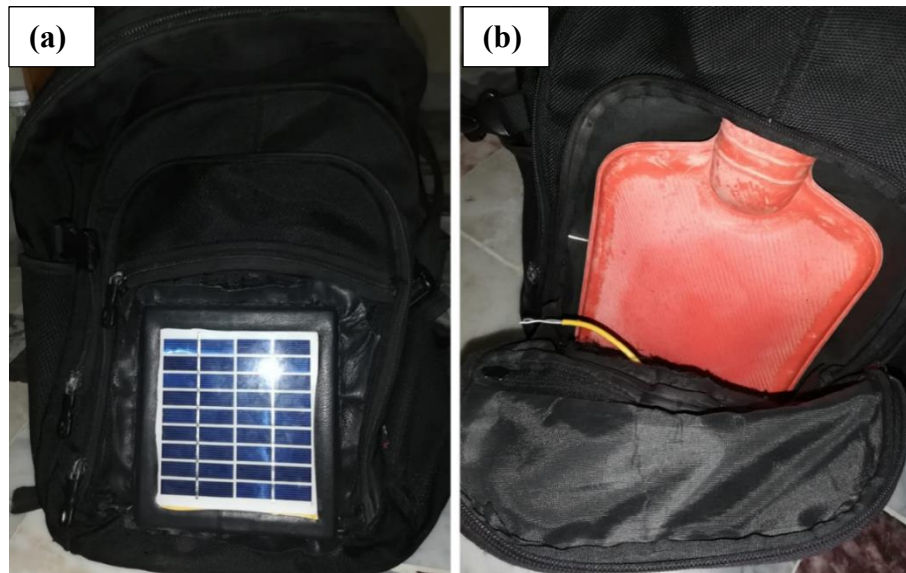


Figure 1. Developed backpack: (a) outer face, (b) water bladder.

2.1 Prototype Configurations

All 4 prototypes share one photovoltaic energy harvester intended for wearable devices. The cell is $8\ \text{cm} \times 11\ \text{cm}$, an area of $88\ \text{cm}^2$, with a rating of $1.7\ \text{W}$ at $8.5\ \text{V}$ and $200\ \text{mA}$, as listed in table 1. Values at open circuit and at short circuit are not given by the manufacturer.

Table 1. Photovoltaic cell specification.

Specification	Unit	Data
Maximum power current	mA	200
Maximum power voltage	V	8.5
Rated power	W	1.7
Rated test temperature	°C	25
Width × length × thickness	cm	8 × 11 × 0.2

In prototype 1 the harvester is mounted on the outer face of the backpack without a bladder. In prototype 2 the rubber bladder filled with tap water sits between the cell and the backpack, keeping the cell nearer to the ambient temperature in hot weather while the water stays drinkable. Prototypes 3 and 4 use the same bladder with iced water and hot water, respectively, giving rear surface temperatures from approximately 0 °C to 60 °C.

Each prototype is tested in 3 environments: direct sunlight outdoors, shade outdoors and artificial light indoors.

2.2 Power Management Circuits

Prototype 1 is tested with 2 power management circuits, whose datasheet parameters are listed in table 2. The BQ25570, mounted on a CJMCU 2557 module, is a boost charger with an integrated buck output intended for sources that supply microwatts to milliwatts [15]. It needs 600 mV to start from a fully discharged state, keeps harvesting down to 100 mV and has a quiescent current of 488 nA. Furthermore, the BQ25570 samples the no load voltage of the source every 16 s and regulates its input to 80% of that sample for solar cells, which keeps the cell near its optimum. The LM2596 is a buck converter with an input range of 4.5 V to 40 V and an output of up to 3 A [16]. It provides no tracking, and its 5 mA quiescent current amounts to approximately 25 mW at a 5 V input.

Table 2. Power management circuit datasheet values.

Parameter	BQ25570 [15]	LM2596 [16]
Topology	Boost charger with buck output	Buck converter
Input range	0.1 V to 5.1 V	4.5 V to 40 V
Cold start input voltage	600 mV	Not applicable
Output range	2 V to 5.5 V	1.23 V to 37 V
Maximum output current	110 mA (buck output)	3 A
Quiescent current	488 nA	5 mA

Maximum power point tracking	80% of open circuit voltage, sampled every 16 s	None
Efficiency (datasheet)	Up to 93%	73% (3.3 V) and 80% (5 V) at 3 A

As both circuits receive the same solar input from prototype 1 and charge the same battery pack, any difference between them comes from the circuits themselves. The cell operates at 8.5 V at its maximum power point, whereas the BQ25570 is recommended for inputs up to 5.1 V, and the CJMCU 2557 module carries no input protection. The BQ25570 is consequently run outside its recommended input range here, and its results are reported as measured. An input protection stage is needed in a practical design. Limiting the cell to 5.1 V with a clamp pulls it off its maximum power point: the simulated curve in figure 3 yields 1.13 W at 5.1 V, or 66% of the 1.70 W peak, whereas a harvester circuit rated for the full cell voltage avoids this penalty. Indoors, the cell supplies no more than 1.39 mW, too little to run the LM2596, whereas outdoors the quiescent current of the LM2596 is small compared with the available power.

3. Mathematical Model of the Photovoltaic Cell

The cell is modeled as a photocurrent source I_{ph} together with a series resistance R_s and a shunt resistance R_{sh} . In practical cells R_s is small and R_{sh} large, and both are frequently neglected. Arrays are formed from modules wired in series or in parallel, as depicted in figure 2.

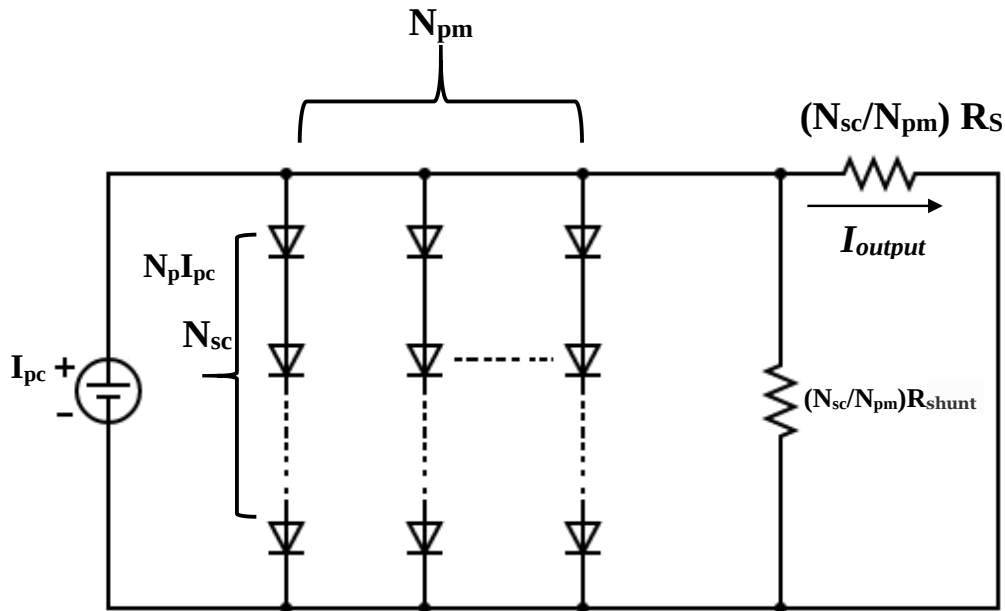


Figure 2. Photovoltaic array circuit.

In the single diode representation, the light generated current flows in parallel with a diode and a shunt path, and a series resistance connects the combination to the terminals. Equations (1) to (6) follow [17], [18].

The photocurrent grows linearly with irradiance and shifts with the cell temperature relative to 298 K:

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times \frac{S_r}{1000} \quad (1)$$

with I_{ph} in A, I_{sc} the short circuit current at 1000 W/m² and 25 °C (A), K_i its temperature coefficient (A/K), T the cell temperature (K) and S_r the irradiance (W/m²).

The reverse saturation current at reference conditions is found from the open circuit point:

$$I_{rs} = \frac{I_{sc}}{\exp(\frac{qV_{oc}}{N_s n k T}) - 1} \quad (2)$$

with q equal to 1.6×10^{-19} C, V_{oc} the voltage at open circuit (V), N_s the count of cells in series, n the ideality factor and k equal to 1.3805×10^{-23} J/K.

Temperature changes the saturation current through the semiconductor band gap:

$$I_o = I_{rs} \left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_g}{n k} \left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad (3)$$

with T_r equal to 298 K and E_g equal to 1.1 eV for silicon.

The photocurrent, the diode current and the leakage through the shunt branch together give the implicit current and voltage relation of the array:

$$I = N_p I_{ph} - N_p I_o \left\{ \exp\left[\frac{V}{N_s n V_t} + \frac{I R_s}{N_p n V_t}\right] - 1 \right\} - I_{sh} \quad (4)$$

with the diode thermal voltage defined as:

$$V_t = \frac{k T}{q} \quad (5)$$

and the shunt branch current given by:

$$I_{sh} = \frac{\frac{V N_p}{N_s} + I R_s}{R_{sh}} \quad (6)$$

with N_p the count of parallel modules, R_s and R_{sh} the series and shunt resistances (Ω) and V_t the diode thermal voltage (V). As I appears on both sides of equation (4), it is solved numerically at each operating point, usually by Newton Raphson or fixed point iteration.

4. Simulation of the Photovoltaic Cell

The cell is modeled in MATLAB Simulink with equations (1) to (6). As the manufacturer quotes only 8.5 V and 200 mA at maximum power, the remaining parameters are estimated: 10.6 V at open circuit, from a voltage ratio of 80% typical of crystalline silicon [15], and 222 mA at short circuit, from a current ratio of 90%. As shown in figure 3 (a), the simulated current is nearly flat at low voltage and drops steeply after the knee, where the output peaks.

As shown in figure 3 (b), the simulated power climbs to 1.70 W at 8.5 V and falls on either side of this point. The measured results are judged against this curve.

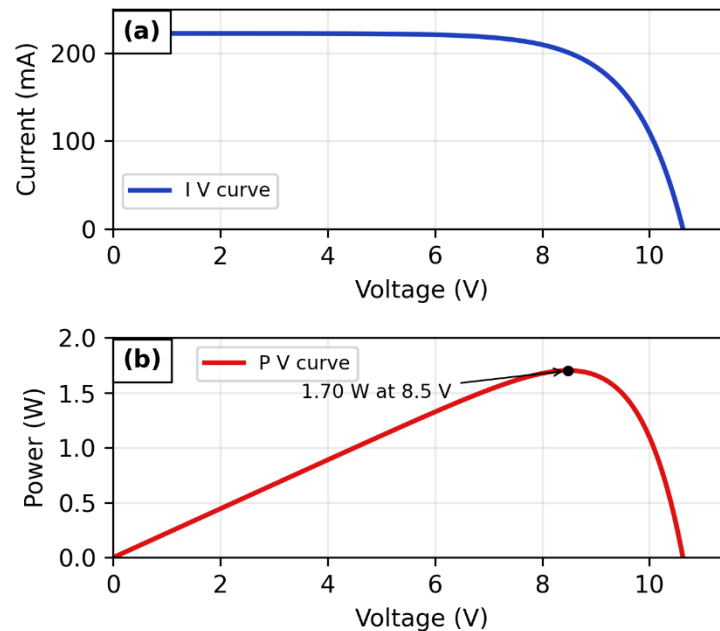


Figure 3. Simulated cell curves: (a) current, (b) power.

5. Experimentation of the Developed Prototypes

The experimental procedure is outlined in figure 4. Four prototype configurations of the backpack are prepared, and every configuration undergoes the complete load sweep under 3 illumination conditions. The electrical and thermal measurements are followed by a comparison of the 2 power management circuits and a benchmark against published harvesters.

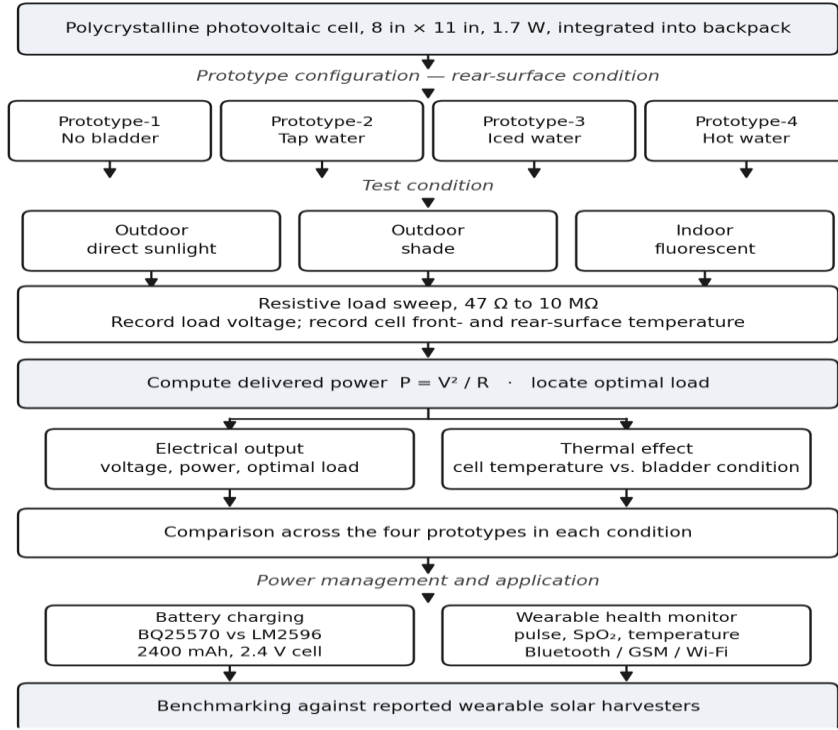


Figure 4. Flow of the experimental methodology.

5.1 Experimental Setup and Measurement Procedure

Testing is carried out in March under 3 conditions: outdoors in direct sunlight, outdoors in shade and indoors under bulb lighting. For every prototype and condition, the load is stepped from 47 Ω to 10 MΩ and the load voltage is read on a UNI-T UT33A+ multimeter. The meter reads DC volts within $\pm(0.5\% + 2 \text{ digits})$ and resistance within $\pm(0.8\% + 2 \text{ digits})$, with an input impedance of 10 MΩ. Readings near 10 MΩ are indicative only, as the meter impedance there is of the same order as the load. Before each run the bladder water is brought to its set temperature, whereas the irradiance and the surface temperatures of the cell are not recorded, and each sweep is carried out a single time. The power P_L and current I_L in the load are calculated from the measured V_L and the resistor value R_L :

$$P_L = \frac{V_L^2}{R_L}, \quad I_L = \frac{V_L}{R_L} \quad (7)$$

Two terms set the uncertainty of P_L : the meter accuracy on V_L and the tolerance of R_L :

$$\frac{\delta P_L}{P_L} = \sqrt{\left(2 \frac{\delta V_L}{V_L}\right)^2 + \left(\frac{\delta R_L}{R_L}\right)^2} \quad (8)$$

where δV_L and δR_L stand for the respective uncertainties, each equal to the meter accuracy on the selected range including its 2 digit term. Across the maximum power points of table 3, the power uncertainty ranges from 1.7% to 2.4%, and the highest power is $1223.3 \pm 21.8 \text{ mW}$. The peak voltage and the peak power do not coincide on the load sweep, and every power value is quoted together with its load and with the voltage measured at that load.

Figure 5 depicts the setup in direct sunlight in part (a), in shade in part (b) and indoors in part (c). Tap water, iced water and hot water are placed in the bladder in sequence, altering the temperature at the back of the cell, while the illumination is held as constant as possible outdoors.

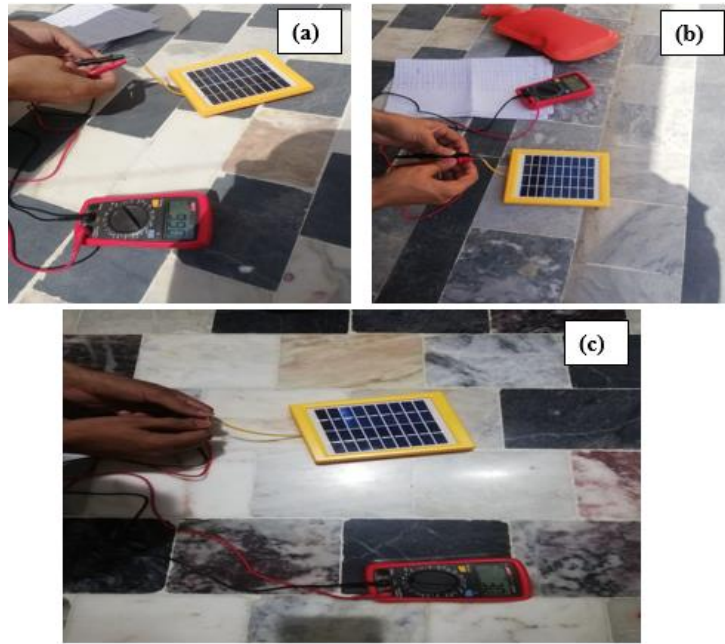


Figure 5. Experimental arrangements: (a) sunny, (b) shade, (c) indoor.

5.2 Outdoor Performance in Direct Sunlight

In direct sunlight, prototype 1 delivers 960.8 mW to a $47\ \Omega$ load, and its output peaks at 1223.3 mW with $73\ \Omega$, where 9.45 V appears across the load, as depicted in figure 6. No other test exceeds this value, which equals 72% of the cell rating of 1.7 W and a power density of $13.9\ \text{mW}/\text{cm}^2$.

Filling the bladder with tap water leaves the output unchanged: prototype 2 also peaks at 1223.3 mW with $73\ \Omega$ and 9.45 V. The rubber wall insulates the cell well enough that water at the ambient temperature produces no measurable change.

With iced water in the bladder, prototype 3 peaks at 905.4 mW at $73\ \Omega$, 26% below prototype 1, and its voltage at $47\ \Omega$ is 5.82 V compared with 6.72 V for prototype 1. The drop runs counter to the gain expected when a crystalline silicon cell is cooled.

Hot water in the bladder gives the weakest result: prototype 4 reaches only 634.0 mW, at $94\ \Omega$ and 7.72 V, which is 48% below prototype 1. Figure 6 plots the voltage of all 4 prototypes against load in part (a) and their power in part (b). Neither a warmed nor a cooled bladder outperforms the bare cell in direct sunlight.

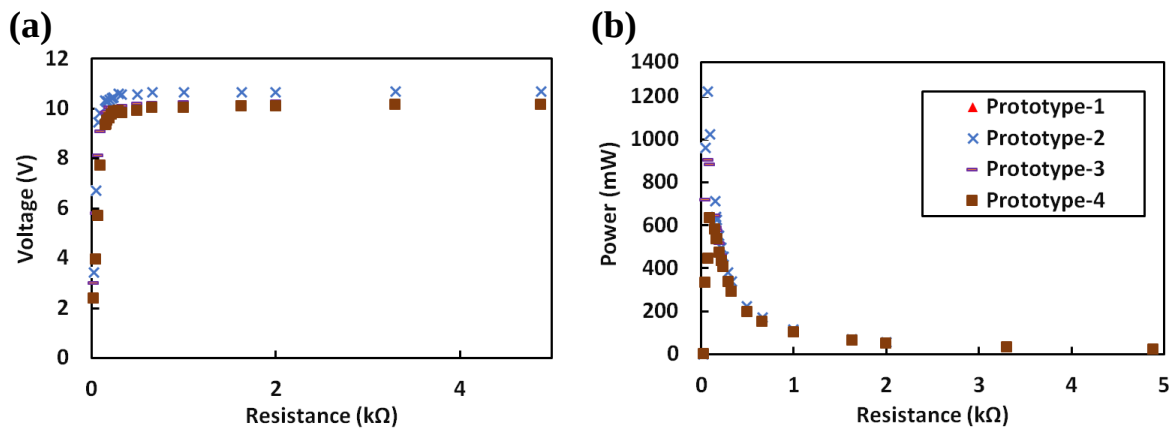


Figure 6. Direct sunlight results: (a) voltage, (b) power.

5.3 Outdoor Performance in Shade

In shade, prototype 1 peaks at 435.0 mW with 195 Ω and 9.21 V across the load, whereas its voltage at 47 Ω is 2.90 V, as depicted in figure 7. Beyond the optimum the power declines steadily with load and reaches 0.01 mW at 10 M Ω .

Prototype 2 once more matches prototype 1, with 179 mW at 47 Ω and a peak of 435.0 mW at 195 Ω .

Prototype 3 peaks at 117.6 mW at 660 Ω with 8.81 V across the load, and prototype 4 reaches 114.9 mW at 660 Ω with 8.71 V. Both remain far below prototype 1, and both decline to 0.01 mW at 10 M Ω .

The ranking of the 4 prototypes in shade repeats that in direct sunlight, whereas the differences widen and prototypes 3 and 4 reach their optimum at a load 3.4 times higher than prototype 1. Figure 7 plots the shaded results, voltage in part (a) and power in part (b).

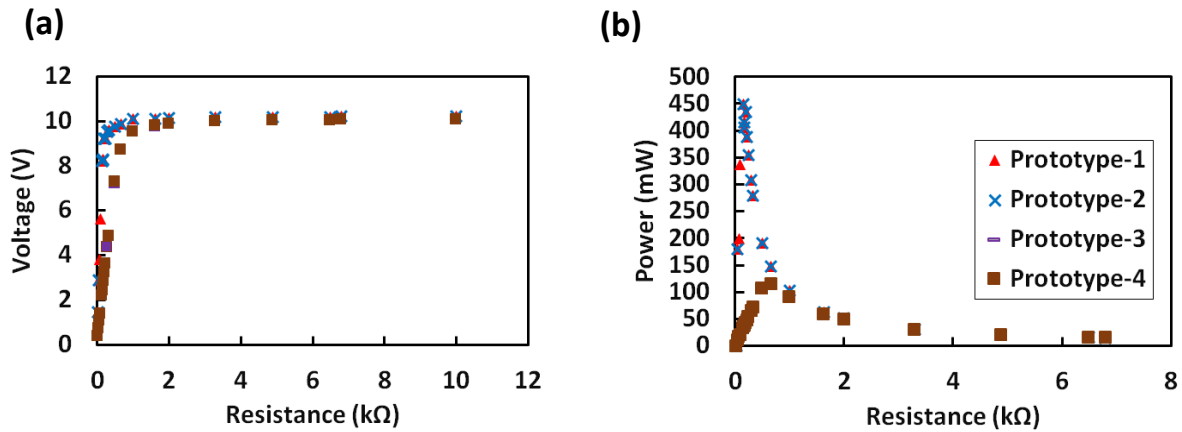


Figure 7. Shade results: (a) voltage, (b) power.

5.4 Indoor Performance

Moving indoors reduces the available power by approximately 3 orders of magnitude, as depicted in figure 8. Prototype 1 peaks at 1.39 mW with 19.42 k Ω and 5.19 V, and its output falls to 0.004 mW with 10 M Ω .

The indoor result of prototype 2, 1.39 mW at 19.42 k Ω and 5.19 V, again coincides with prototype 1.

Prototype 3 supplies 1.058 mW at 33 k Ω and 5.91 V, and prototype 4 supplies 1.028 mW at 26.1 k Ω and 5.18 V.

Under artificial light the photocurrent is far smaller, so the optimal load rises by 3 orders of magnitude, from tens of ohms outdoors to tens of kilohms indoors. The prototypes keep the same ranking, and figure 8 plots their indoor voltage in part (a) and power in part (b).

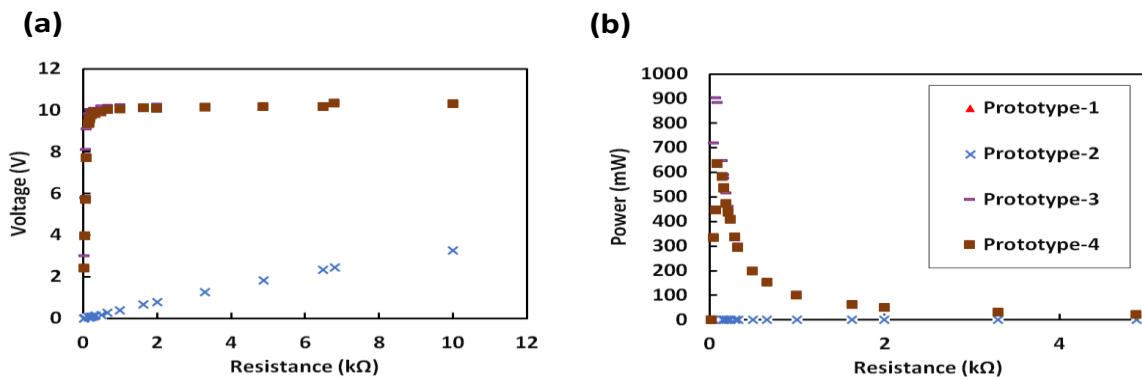


Figure 8. Indoor results: (a) voltage, (b) power.

5.5 Effect of Rear Surface Temperature

Table 3 lists the voltage, current and load of each prototype at its maximum power point, with the current calculated from equation (7). At the maximum power point, the current of a photovoltaic cell scales almost linearly with the irradiance reaching it and increases only slightly with temperature, through the coefficient K_i in equation (1). The voltage, on the other hand, drops as the temperature rises, due to the increase in the saturation current in equation (3). Comparing the 2 quantities distinguishes an optical loss, seen as a lower current, from a thermal loss, seen as a lower voltage.

Table 3. Maximum power points of the 4 prototypes.

Condition	Prototype	Load (Ω)	Voltage (V)	Current (mA)	Power (mW)
Direct sunlight	1	73	9.45	129.5	1223.3
Direct sunlight	2	73	9.45	129.5	1223.3
Direct sunlight	3	73	8.13	111.4	905.4
Direct sunlight	4	94	7.72	82.1	634.0
Shade	1	195	9.21	47.2	435.0
Shade	2	195	9.21	47.2	435.0
Shade	3	660	8.81	13.3	117.6
Shade	4	660	8.71	13.2	114.9
Indoor	1	19420	5.19	0.267	1.390
Indoor	2	19420	5.19	0.267	1.390
Indoor	3	33000	5.91	0.179	1.058
Indoor	4	26100	5.18	0.198	1.028

Under direct sunlight, prototype 3 carries 111.4 mA at its maximum power point compared with 129.5 mA for prototype 1, 14% lower, and its current at 47 Ω drops by 13% from 143.0 mA to 123.8 mA. Cooling cannot cause a drop of this size, as the short circuit current of crystalline silicon varies by less than 0.1% per K. The loss with iced water is linked to a reduction in the light reaching the cell. Condensation forming on the cell cover once it is cooled below the dew point, and a change in the cell tilt as the bladder deforms, are the probable causes, and both need confirmation through logged irradiance and surface temperatures. Similarly, prototype 4 shows a 37% fall in current to 82.1 mA and an 18% fall in voltage to 7.72 V. The voltage drop agrees with heating, whereas the current drop does not, and the 48% power loss is larger than the thermal loss given by the power temperature coefficient:

$$P = P_{\text{ref}}[1 + \gamma(T_c - T_{\text{ref}})] \quad (9)$$

where T_{ref} is the 25 °C reference, P_{ref} is the power at T_{ref} , T_c is the operating temperature of the cell and γ is the relative change of power per kelvin, approximately -0.4% to -0.5% per K for crystalline silicon [19]. Even a 35 K increase in cell temperature reduces the power by just 14% to 18% according to equation (9). In shade, prototypes 3 and 4 carry a current approximately 3.5 times lower than prototype 1, a sign that the shaded runs are made under unequal irradiance. Indoors, prototype 3 shows 5.91 V at its maximum power point, higher than the 5.19 V of prototype 1 as a cooler cell would, whereas its current is 33% below that of prototype 1. With no logged irradiance or surface temperatures and only one run per condition, the mechanisms deduced from current and voltage remain indicative, and repeated runs with logged irradiance and temperatures are needed to confirm them. The rubber bladder fails to increase the harvested power under every condition tested, and the losses with iced and hot water stem mainly from a current reduction that the cell temperature cannot explain on its own.

5.6 Battery Charging

A 2400 mAh pack of 2 AA cells in series, with a nominal voltage of 2.4 V, is charged from prototype 1 at 25 °C ambient, first through one power management circuit and then through the other. Each charge starts from a deeply discharged pack at 0.2 V. A lossless converter fed with 1223.3 mW could push at most approximately 437 mA into the pack at 2.8 V, so a 55 min charge restores no more than approximately 400 mAh, 17% of the capacity. The pack voltage describes only the start of charging, and a pack at 2.4 V is not a charged pack.

As shown in figure 9, the pack voltage reaches 2.4 V after 5 min with the LM2596 and after 11 min with the BQ25570, approximately twice the time. By the end of the run, the LM2596 has taken the pack to 2.86 V in approximately 53 min and the BQ25570 to 2.80 V in approximately 55 min. Outdoors the LM2596 is faster, consistent with its larger current capability at the cell voltage in sunlight, whereas the BQ25570 remains in its inefficient cold start mode until its storage element reaches 1.8 V [15]. The strength of the BQ25570 lies in starting from 600 mV with a quiescent current of only 488 nA, which decides the choice indoors, where the cell gives 1.39 mW and cannot meet the 5 mA quiescent demand of the LM2596. The input and output currents are not measured, so the comparison relies on how fast the pack voltage rises under the same sunlight, and the efficiencies quoted are the datasheet values in table 2. Moreover, the BQ25570 is operated above its recommended input voltage, so its results apply to the present cell only.

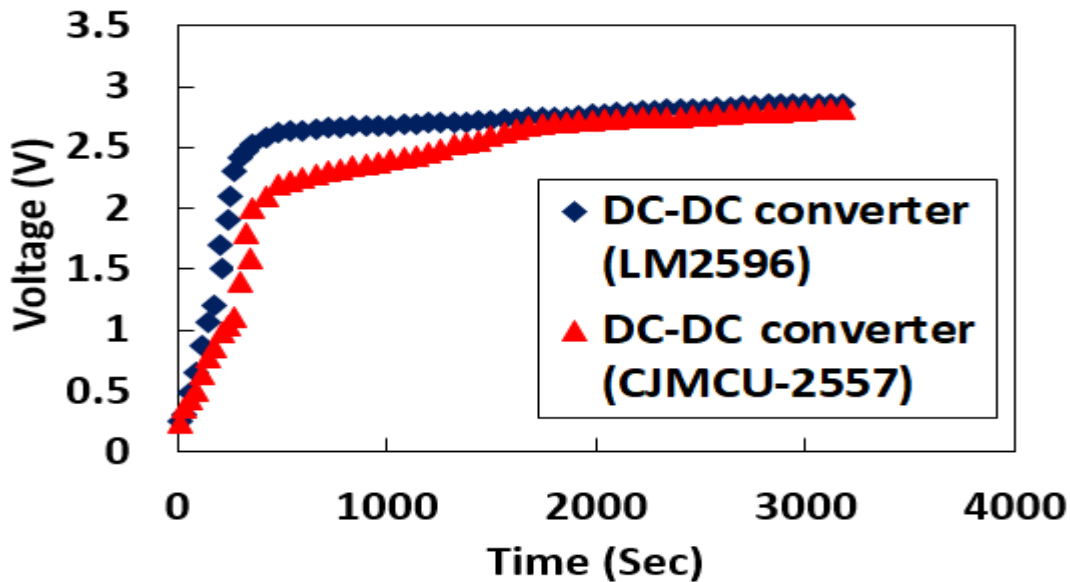


Figure 9. Battery pack voltage during charging.

6. Comparative Analysis

Table 4 sets the present work against solar harvesters reported for wearable use in terms of cell area, load voltage, delivered power and power density.

Cell areas vary greatly across the compared work, from 7.68 cm² in [5] up to 2445.5 cm² in [4], and power density is the more equitable measure. The present cell reaches 13.9 mW/cm², whereas the flexible module of [10] reaches 6.58 mW/cm², the harvesters of [5], [8] and [9] approximately 2.1 mW/cm² and the jacket of [4] 0.52 mW/cm². The advantage is due to the rigid polycrystalline cell, whereas the other harvesters adopt flexible cells that sacrifice efficiency for conformability. The values reported elsewhere are obtained under differing illumination and are not all quoted at a matched load, which limits the comparison.

Most of the compared harvesters drive a physiological sensor: photoplethysmography for blood oxygen in [5], a pulse sensor in [6], electromyography in [8] and a body monitoring unit in [4]. Table 4 summarizes each harvester, with power in mW and power density in mW/cm².

Table 4. Benchmark against published wearable solar harvesters.

Type	Size (cm ²)	Voltage (V)	Power (mW)	Power density (mW/cm ²)	Ref.
Flexible	7.68*	4.5	16	2.08*	[5]
Flexible	2445.5*	—	1282.57	0.52*	[4]
Flexible	—	2.7	120.7	—	[6]
Flexible	43.2*	0.882	0.056	0.0013*	[7]
Flexible	7.68*	3.3	16*	2.08*	[8]
Flexible	20.24*	5.14	43.4*	2.14	[9]
Flexible	76*	4.5	500	6.58*	[10]

Flexible	117	—	93.9	0.80*	[11]
Rigid	88	9.45	1223.3	13.9	[This work]

*Derived from data given in the cited study.

7. Conclusion

In summary, we have developed a backpack that powers itself from a polycrystalline photovoltaic cell on its outer face, with a rubber water bladder placed behind the cell. The 4 prototypes are tested in direct sunlight, in shade and indoors with loads from 47 Ω to 10 M Ω . The best result, 1223.3 mW or 13.9 mW/cm² at 73 Ω in direct sunlight, comes from prototypes 1 and 2, in which the temperature of the cell is not altered. With iced water and hot water the power drops to 905.4 mW and 634.0 mW, respectively, and the same order is kept in shade and indoors. Both drops are traced mainly to a lower current at the maximum power point, a sign of less light at the cell, whereas the voltage moves with the water temperature in the expected sense wherever the data resolve it. The bladder serves well as a water carrier, whereas it brings no gain in harvested power under any condition tested. Between outdoor and indoor use the optimal load changes from tens of ohms to tens of kilohms, and a power management stage meant for both must handle this range. In direct sunlight the LM2596 takes a 2400 mAh pack to 2.4 V in 5 min, against 11 min with the BQ25570, whereas the BQ25570 starts from 600 mV, draws only 488 nA and is the better choice indoors. As the cell voltage exceeds the recommended BQ25570 input, a practical design requires either input protection or a harvesting circuit rated for the voltage of the cell.

References

- [1] A. S. Khan and F. U. Khan, "A survey of wearable energy harvesting systems," *International Journal of Energy Research*, vol. 46, no. 3, pp. 2277–2329, 2021, doi: 10.1002/er.7394.
- [2] S. Bakhtiar, F. U. Khan, W. U. Rahman, A. S. Khan, M. M. Ahmad and M. Iqbal, "A pressure-based electromagnetic energy harvester for pipeline monitoring applications," *Journal of Sensors*, vol. 2022, art. 6529623, pp. 1–16, 2022, doi: 10.1155/2022/6529623.
- [3] A. S. Khan and F. U. Khan, "Experimentation of a wearable self-powered jacket harvesting body heat for wearable device applications," *Journal of Sensors*, vol. 2021, art. 9976089, pp. 1–22, 2021, doi: 10.1155/2021/9976089.
- [4] A. S. Khan and F. U. Khan, "A wearable solar energy harvesting based jacket with maximum power point tracking for vital health monitoring systems," *IEEE Access*, vol. 10, pp. 119475–119495, 2022, doi: 10.1109/ACCESS.2022.3220900.
- [5] P. Jokic and M. Magno, "Powering smart wearable systems with flexible solar energy harvesting," in *Proc. IEEE Int. Symp. Circuits and Systems (ISCAS)*, 2017, doi: 10.1109/ISCAS.2017.8050615.
- [6] T. Wu, M. S. Arefin, J.-M. Redouté and M. R. Yuce, "A solar energy harvester with an improved MPPT circuit for wearable IoT applications," in *Proc. EAI Int. Conf. Body Area Networks*, 2016, doi: 10.4108/eai.15-12-2016.2267622.
- [7] W. Y. Toh, Y. N. Tan, W. Y. Koh and L. Siek, "Autonomous wearable sensor nodes with flexible energy harvesting," *IEEE Sensors Journal*, vol. 14, no. 7, pp. 2299–2306, 2014, doi: 10.1109/JSEN.2014.2309900.

- [8] V. Kartsch, S. Benatti, M. Mancini, M. Magno and L. Benini, "Smart wearable wristband for EMG based gesture recognition powered by solar energy harvester," in Proc. IEEE Int. Symp. Circuits and Systems (ISCAS), 2018, doi: 10.1109/ISCAS.2018.8351727.
- [9] A. Satharasinghe, T. Hughes-Riley and T. Dias, "An investigation of a wash-durable solar energy harvesting textile," Progress in Photovoltaics, vol. 28, no. 6, pp. 578–592, 2020, doi: 10.1002/pip.3229.
- [10] T. V. Tran and W. Y. Chung, "High-efficient energy harvester with flexible solar panel for a wearable sensor device," IEEE Sensors Journal, vol. 16, pp. 9021–9028, 2016, doi: 10.1109/JSEN.2016.2616114.
- [11] K. A. Kim et al., "Design considerations for photovoltaic energy harvesting in wearable devices," Scientific Reports, vol. 12, art. 18143, 2022, doi: 10.1038/s41598-022-22232-x.
- [12] M. M. Sandhu, S. Khalifa, K. Geissdoerfer, R. Jurdak and M. Portmann, "SolAR: Energy positive human activity recognition using solar cells," in Proc. IEEE Int. Conf. Pervasive Computing and Communications (PerCom), 2021, pp. 1–10, doi: 10.1109/PerCom50583.2021.9439128.
- [13] J. Taverne, F. Muhammad-Sukki, A. S. Ayub, N. Sellami, S. H. Abu-Bakar, N. A. Bani, A. A. Mas'ud and D. Iyi, "Design of solar powered charging backpack," International Journal of Power Electronics and Drive Systems, vol. 9, no. 2, pp. 848–858, 2018.
- [14] K. K. Selim, S. Khalid, D. El-nawam, M. Abdel Fattah and D. A. Saleeb, "Solar energy harvesting-based built-in backpack charger," Energy Harvesting and Systems, vol. 11, no. 1, art. 20230114, 2024, doi: 10.1515/ehs-2023-0114.
- [15] Texas Instruments, "bq25570 nano power boost charger and buck converter for energy harvester powered applications," Datasheet SLUSBH2G, Mar. 2019.
- [16] Texas Instruments, "LM2596 SIMPLE SWITCHER power converter 150-kHz 3-A step-down voltage regulator," Datasheet SNVS124G, Mar. 2023.
- [17] H.-L. Tsai, C.-S. Tu and Y.-J. Su, "Development of generalized photovoltaic model using MATLAB/SIMULINK," in Proc. World Congress on Engineering and Computer Science (WCECS), San Francisco, USA, 2008, pp. 846–851.
- [18] T. Salmi, M. Bouzguenda, A. Gastli and A. Masmoudi, "MATLAB/Simulink based modeling of photovoltaic cell," International Journal of Renewable Energy Research, vol. 2, no. 2, pp. 213–218, 2012.
- [19] E. Skoplaki and J. A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations," Solar Energy, vol. 83, no. 5, pp. 614–624, 2009, doi: 10.1016/j.solener.2008.10.008.