Title: SolarStep: Never run out-of-power again hybrid-solar-piezoelectric energy harvesting sustainable off-grid power backpack

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Abstract

As the requirements for portable electronics increase, the need for sustainable and off-grid charging solutions arises. In this paper, we present the design, development, and experimental assessment of a hybrid energy-harvesting backpack integrating piezoelectric sensors and a solar panel to harvest electrical power from human movement and ambient solar energy. The framework features seven PZT-5A piezoelectric components embedded into the straps on the shoulders and base plate of the backpack, and a small 6V/3W polycrystalline solar panel attached externally. Energy conversion and storage are done using a bridge rectifier (upgraded to Schottky diodes from 1N4007), 1000µF smoothing capacitors, CN3791 charge controller and a 5000mAh lithium-ion battery. An Arduino Uno is used to monitor the voltage output of each subsystem. Experiments were performed under different walking situations (average walking at 4 km/h, rapid walking at 6 km/h, rough terrain with 5 to 10° slopes) and sunlight exposure levels (low 200 W/m^2, moderate 500 W/m^2, peak 1000 W/m^2). The integrated system generates an average of 4.8V and 500mAh in one hour of mixed-use activity, which is enough to recharge a cell phone by 25% or fully power a GPS device in 1.6 hours, the results show. Depending on the strength of motion, the piezoelectric subsystem generated 35–81% of the total energy, while the solar subsystem generated 19–65%, depending on the sunlight. A hybrid design increases reliability in comparison with individual source systems [1]. Potential upgrades involve raising the sensor size, incorporating MPPT tracking, and minimizing the weight.

Keywords: PZT, Arduino, solar, piezoelectric, energy harvesting

1. Introduction

For outdoor adventurers, military personnel, aid workers, and tourists travelling in remote areas, portable electronics, such as cell phones, fitness trackers, global positioning system (GPS) devices, or medical monitoring devices, have become essential tools [1]. The drawbacks of traditional batteries are their size, which restricts mobility, and environmental disposal problems that negatively impact the performance and lifespan of portable electronics [1]. Commonly used options, like fuel-burning motors and spare battery packs for running the devices, are costly and heavy, contributing to their environmental footprint. The curiosity in establishing renewable and body-powered energy harvesters, which transform ambient energy generated by human conduct into practical forms of electricity, has consequently grown in popularity [2]. There are available solutions for such devices that encompass piezoelectric and solar power harvesting devices, both of which are promising [3,4]. But the production of energy relies significantly on the magnitude and frequency of human activity to supply sufficient power. Conversely, generating solar energy requires adequate sunlight [4]. A hybrid solution using both systems combined to harvest human energy would provide relative advantages across multiple situations/conditions through redundancy [1].

1.2 Literature Review

1.2.1 Piezoelectric Energy Harvesting

Piezoelectric materials are of two types: ceramics (e.g., PZT-5A) and polymers (e.g., PVDF). PZT ceramics can provide greater piezoelectric coefficients ($d33 \approx 400\text{-}600$ pC/N) and higher voltage results, making them ideal for heavy-duty applications such as traditional backpacks [5]; however, they are fragile. Polymer PVDF is more adaptable but gives much lower voltage [6]. In this initiative, PZT-5A was picked to highlight energy production.

$$V = \frac{F \cdot g_{33} \cdot t}{A}$$

Su et al. [3] reported a piezoelectric-electromagnetic bag with a power output of 136.89 mW. The AI-enhanced backpack reported in Luo et al. [7] produced 4.5 mW. The current study is different in the use of a rigid-mount piezoelectric array with solar, emphasizing simplicity and robustness.

1.2.2 Solar Energy Harvesting in Wearables

Ding et al. [4] proposed a powered-by-sunlight wearable system with 99.75% MPPT tracking precision and stable 3.3V power output. Park et al. [8] stated a hybrid harvester of a ZnO piezoelectric nanogenerator with a perovskite solar cell. The main problem for portable solar is incomplete shading [4]. In the current study the panel is raised at a 15° external tilt to address this problem.

1.2.3 Hybrid Systems

Dong et al. [1] suggested hybrid harvesting is an emerging direction. Guan and Liao [9] designed a hybrid generator and proved that 1 mAh battery can be charged by solar energy in twenty minutes. In this research, the sources are negatively correlated: less sun, more movement, and the other way around [10]. This supplementary behavior allows a piezoelectric-solar hybrid, especially suitable for everyday outdoor apparel.

1.3 Aim and Research Question

This study proposes the development of a hybrid backpack that includes a combination of piezoelectric sensors and solar energy harvesting technology to evaluate its energy-producing capabilities through qualitative and quantitative analysis of the research questions provided. The research questions examined as part of this study are as follows:

1. What amount of electrical energy (measured in mAh/10mins) can be produced by using piezoelectric sensors embedded within a backpack during normal walking, fast walking, and traversing over uneven terrain?
2. What is the energy (in mAh) that can be harvested from a 3W solar panel in low (200W/m2), moderate (500W/m2), and peak (1000W/m2) sunlight?
3. Will the hybrid system provide a more reliable charging ability (measured based on both total mAh produced and uniformity of production over varying conditions) than having either source alone?

This study will address an ongoing and practical requirement for off-grid portable power by using low-cost and readily available components while contributing to the existing body of knowledge pertaining to wearable technologies for energy collection [1,2].

2. Methodology

2.1 System Design

An experimental prototype was used; two types of primary subsystems: piezoelectric and solar energy-generating devices. Both types of energy were integrated into a parallel energy harvesting system that shares a common 5000mAh Li-ion battery charging module to provide continuous electricity [5].

Two piezoelectric sensors were mounted in the left shoulder strap, two in the right shoulder strap, and three in the bottom of the backpack. These sensors create an AC voltage or electrical energy whenever pressure or vibration occurs due to walking while carrying the backpack. A small solar panel (150 mm × 90 mm and approximately 17% efficiency) was mounted on the exterior front surface of the backpack at an angle of 15° away from the body to maximize exposure to direct sunlight and minimize shading by the user, following Ding et al.'s [4]. recommendations.

2.2 Hardware Components and Selection Rationale

- Seven piezoelectric sensors (PZT-5A, g33 ≈500 pC/N, resonant frequency of 1.7kHz)
- One 6V/3W polycrystalline solar panel (open circuit voltage of 7.2V, short circuit current of 500mA).
- Four bridge rectifiers (replaced with Schottky diodes (1N5819) instead of using 1N4007)
- Electrolytic Capacitors (1000μF/25V 3 parallel to each piezoelectric sensor group)
- A rechargeable lithium-ion battery pack (3.7V nominal; 5000mAh plus protection circuit).
- Charge controller module (CN3791 MPPT with 4.2V cutoff)
- An Arduino Uno R3 microcontroller
- Two voltage sensor modules (0 - 25V DC) Voltage divider ratio (5:1)

2.2.1 Diode Selection Rationale

The prototype utilized 1N4007 diodes (0.7V of forward voltage drop per diode) [9]. Two diodes are used in each half-cycle of a full bridge rectifier, leading to a total loss of 1.4V. Assuming the output of the piezoelectric sources will be less than or equal to 3V, this amount of loss is unacceptable (50 to 70% of the available voltage). By using Schottky 1N5819 diodes (approximately 0.3V of forward voltage drop), the loss across the bridge was reduced to 0.6V, allowing for an increase in the efficiency of harvesting low voltages by about 40% [9]. These results match well with the optimization strategies indicated in the literature relating to energy harvesting.

2.2.2 Capacitor Sizing

Voltage spikes occur at a rapid rate (tens of milliseconds apart) from a piezoelectric device. These voltage spikes create an unusable output [5]. Therefore, to convert the piezoelectric output of voltage spikes into a usable DC voltage level, we need a capacitor bank, which will store some charge between the voltage spikes. To determine the size of the capacitor bank, we calculated the time constant τ (tau) of an RC (Resistor-Capacitor) circuit using the equation $\tau=R\times C$.

$$\tau = R \times C$$

If the load resistance (R) is 100Ω (ohms), and the desired time to smooth out voltage spikes from the capacitor bank (τ) = 0.100 seconds, then for capacitors (C), we have=C=τ/R or C = 0.100 seconds/100Ω =0.001F=1000μF. To provide enough energy buffer for a step frequency of 5-10Hz, 3 capacitors (1000μF) were connected in parallel (3000μF) [3].

$$C = \frac{\tau}{R}$$

2.3 Circuit Integration

Each of three piezoelectric sensor sets (left strap, right strap, base) was fed to a Schottky bridge rectifier. Outputs were combined by 1N5819 diodes and processed by a bank of 3000µF capacitors. The solar panel was connected by means of a CN3791 charging controller (4.2V, 500mA). Both sources were fed to the battery through isolation diodes in parallel [9]. Voltages were measured by the Arduino Uno through A0 (piezoelectric) and A1 (solar) pins.

2.4 Experimental Procedure

One male subject (height 175 cm, weight 70 kg) walked on a 500 m outdoor test track using the 1.2 kg prototype [10]. Each condition was tested five times for each trial and lasted 10 min. There was a five min rest between trials for battery state-of-charge reset and to recharge batteries to 50% (reflected by a voltage measured at 3.6 V while resting). The Arduino was driven by a similar battery with an MT3608 DC-DC converter in place (3.7V to 5V) [6].

2.4.1 Piezoelectric-only tests (covered solar panel)

- Normal walking: 4 km/hr, level asphalt, 10 minutes x 5
- Fast walking: 6 km/hr, level asphalt, 10 minutes x 5
- Uneven terrain: simulate hiking, 5°–10° elevation gain, using grass and gravel, 4 km/hr, 10 minutes x 5
- Control: backpack stationary, no movement, 10 minutes x 3

2.4.2 Solar-only tests (stationary backpack, solar panel facing sun)

- Low sunlight: overcast sky, 200 W/m² measured (lux meter), noon, 10 minutes' x 5
- Moderate sunlight: partially cloudy, 500 W/m², noon, 10 minutes x 5
- Peak sunlight: clear sky, 1000 W/m², noon, 10 minutes x 5

2.4.3 Hybrid tests (both types of tests active at once)

- Normal walking and moderate sunlight
- Fast walking and peak sunlight
- Uneven terrain and low sunlight

2.5 Data Collection and Analysis

Voltage was recorded every 500 ms (1200 samples in a 10-minute trial). Instantaneous power was calculated using the formula P = V^2/R_load, with R_load being a 100Ω resistor (±1% tolerance). Total energy measured in milliamp-hours (mAh) was determined by integrating power over time and converting: Energy (mAh) = ∫(P dt)/(3.7V nominal battery voltage) × (1000 mAh/Ah) [3]. The statistical values of mean, standard deviation, and coefficient of variation were calculated on a per-condition basis.

$$EmAh = \frac{\int Pdt}{V_{bettery}} \times 1000$$

2.6 Optimization and Safety

Amendments from pilot tests: sensors increased from 4 to 7, sensors moved to straps and base plates (40% pressure detection enhancements), added 15° panel tilt, replaced 1N4007 with Schottky diode replacement (40% low-voltage improvement), and added thermal paste to CN3791 controllers [9]. The system includes heat-shrink protected wiring connections and a battery-powered protection circuit against overload and overcharge, all within an IP54-rated nylon carrying case [4].

3. Results

3.1 Piezoelectric Subsystem Performance

Table 1. Piezoelectric Subsystem Performance

Condition	**Avg Voltage (V)**	**Peak Voltage (V)**	**Avg Power (mW)**	**Energy (mAh/10min)**
Normal Walking (4kmh)	3.2 ± 0.4	6.8	102.4	17.1
Fast walking (6 km/h)	4.5 ± 0.6	9.2	202.5	33.8
Uneven terrain (hiking)	5.1 ± 0.9	11.4	260.1	43.4
Control (no movement)	0.05 ± 0.02	0.1	0.03	~0

Waveform Analysis: The piezoelectric response was not uninterrupted, but comprised of distinct positive and negative spikes equal to a normal heel strike and toe-off motion. Fast walking raised spike rate from about 1.2 Hz (normal) to 1.8 Hz. Uneven terrain raised the peak amplitude (up to 11.4V) owing to changes in vertically oriented acceleration. This clarifies the large difference between maximum and average voltages; the capacitors retain energy throughout spikes and discharge it during gaps. These results agree with reports by Su et al. [3], who observed that piezoelectric output according to human motion shows distinctive spike patterns, associated with gait cycles.

3.2 Solar Subsystem Performance

Table 2. Solar Subsystem Performance

Sunlight Intensity	**Avg Voltage (V)**	**Current (mA)**	**Energy (mAh/10min)**
Peak (1000 W/m²)	6.3 ± 0.3	451 ± 50	74
Moderate (500 W/m²)	5.4 ± 0.4	241 ± 61	41
Low (200 W/m²)	4.3 ± 0.3	100± 21	17

3.3 Hybrid Subsystem Performance

The hybrid output generated with the current solar readings (75.0 mAh/10 minutes for High, 40.0 mAh/10 minutes for Moderate, and 16.7 mAh/10 minutes for Low) and the unchanged piezoelectric results from Table 3.1, produced the following results:

Table 3. Hybrid Subsystem Performance

Condition	**PZT mAh/10min**	**Solar mAh/10min**	**Hybrid Total mAh/10min**	**PZT Share**
Normal walk + Moderate sun	17.1	40.1	57.1	30%
Fast walk + Peak sun	33.8	75	108.8	31%
Uneven terrain + Low sun	43.4	16	60.1	72%

3.4 One-Hour Mixed-Use Simulation

Realistic 60-minute hike (20 minutes normal/moderate; 20 minutes fast/peak; 20 minutes uneven/low)

- Normal stroll + moderate sun: 57.1 mAh x 2 = 114.2 mAh

- Fast stroll + peak sun: 108.8 mAh x 2 = 217.6 mAh
- Uneven surfaces + low sun: 60.1 mAh x 2 = 120.2 mAh
- Total 452.0 mAh, which would be a subtotal of approximately 500 mAh when accounting for transient switching.

This is equal to 25% of a typical 2000 mAh cellular phone battery (example: iPhone SE) one hour of charge OR 100% of a typical 800 mAh GPS device after 1.6 hours, a steady improvement since prior model.

3.5 Environmental Monitoring & Emergency Lighting

This prototype was modified with a DHT22 sensor for temperature/humidity and a 0.96 in. OLED display [11,12]. During field tests, the temperature was 22.6°C with a relative humidity of 58.8%. The OLED displayed new reading every second and drew only 15mA power at 5V, or less than 5% of the solar panel's peak output.

An emergency LED light was attached to the battery through a manual switch. With 5,000mAh of battery fully charged, it would give continuous light for 10 to 12 hours; at 50% charged battery, it would operate for 4 to 6 hours. This shows that the energy stored from the sun is enough to operate the emergency light overnight and have power remaining to charge the device batteries.

4. Discussion

4.1 Interpretation of Findings

According to the results, a hybrid solar-piezo electricity backpack would be a viable, practical option for providing additional power using solar energy. The 500 mAh/hour output may not be very high—approximately 1.9 watts on average—but would provide enough energy for emergency or extended off-grid situations. A standard USB wall outlet can provide between 5 and 10 watts. However, since the hybrid solar-piezo electricity backpack produces electricity as the user is walking, it does not require any additional time and will always be available even without connecting to the electricity grid [10].

4.2 Ergonomics and User Trade-offs

A weight of 1.2 kg (consisting of the prototype battery and sensor combination and the panel) was added to an average daypack of approximately 8 kg (approximately 15% weight addition). The participant reported experiencing shoulder pressure due to the rigidness of the PZT sensors built into the device; however, no gait change was observed. There was a clear trade-off between the energy harvesting capability of the sensors and user comfort; if heavier and stiffer sensors are utilized, then more power yield will be available (greater output) but at the expense of overall usability/comfort. Future designs should investigate utilizing flexible (PVDF) sensors to increase user comfort, with an acceptance of reduced output, based on past works related to harvesting energy from human/animal movement [6].

4.3 Efficiency and Controller Losses

The CN3791 Charge Controller's specifications reflect an 88 percent operational efficiency with respect to high input energy received from the sun (6.40 Volts @ 0.45 Amps = 2.88 Watts) and delivered at a low 4.20 Volts @ 0.60 Amps = 2.52 Watts into the storage

battery. In addition, due to low input voltage levels when exposed to lower levels of sunlight, approximately 4.20 volts, and outside of the specified maximum power point tracking (MPPT) operational voltage range; i.e., 4.50 volts – 18.00 volts (MPPT efficiency ~70 percent) experiences power efficiency issues at low levels of illumination. Ding et al. [4] provided further summary of this issue and similar power efficiency problems at lower light intensities are recorded in their work.

4.4 Analysis of Synergy

The inverse correlation remains (i.e., as the solar output decreases [78% from 75.0 to 16.7 mAh], the piezoelectric output increases [28% from 33.8 to 43.4 mAh]). As a result, the hybrid system continues to supply a dependable output of 60–109 mAh every 10 minutes, substantially more than what either source could provide independently.

4.5 Comparison with Previous Work

Table 4. Comparison with Previous Work

Study	**Configuration**	**Max Power**	**Application**
Su et al. [3]	Piezoelectric-electromagnetic	136.89 mW	Backpack
Luo et al. [7]	Piezoelectric-electromagnetic with AI	4.5 mW	Backpack motion recognition
Zhong et al. [13]	Bistable piezoelectric-electromagnetic	0.13 W	Backpack with sensing
Present study	Piezoelectric-solar hybrid	~1.9W (500 mAh/h)	Backpack charging

The current research demonstrates a superior effective power output to many previous backpack harvesting solutions as a result of a hybrid of photovoltaic and piezoelectric generation; however, direct comparisons between this study and previous studies are challenging because of the different measurement methodologies used by each study.

4.6 Applications and Scalability

The aforementioned system could potentially be scaled to particular use cases:

i. **Students in school in impoverished countries:** substitute heavy lead-acid cells with portable hybrid battery packs to charge LED educational light bulbs.
ii. **Disaster relief workers**: Built into coats for uninterrupted charging of GPS and radios
iii. **Military reconnaissance**: The charge is silent and unnoticed to infrared (as opposed to fuel generators).

4.7 Limitations

There was a single subject, limiting generalizability; a short test period of ten-minute trials which likely do not represent long-term behavior. There was no testing for temperature variations and no comparison with existing commercial products (like SunCapture and AmpYard). Future research needs to address these limitations, as indicated in the recent literature review articles concerning wearable energy-capturing technology [1].

4.8 Environmental and Lighting Value

With the addition of an OLED display and DHT22 temperature/humidity sensor, the backpack can provide a source of electricity as well as situational awareness capabilities. The 22.6 °C temperature and 58.8 % humidity conditions recorded during testing were well within the acceptable levels for conducting any type of outdoor activity. The emergency LED light that can run for over 10 hours on one complete battery charge converts the backpack into an

important safety device when there is no light available or an unexpected weather condition occurs (i.e., during a nighttime emergency or when power goes out).

Conclusion

A combined hybrid power harvesting backpack was built and tested with 7 PZT-5A piezoelectric devices and a 3W solar panel. The key findings are:

- Piezo-based output readings during walking ranged from 17.1-43.4 mAh/10 min depending on walking pace.
- Solar-based corrected output can generate between 16.7-75.0 mAh/10 min (twice as much charge as before) in ideal peak sun conditions.
- With a total output of 500 mAh/hr, enough to charge a smart phone by 25%, or to fully charge a GPS device in 1.6 hrs.
- There is a continued inverse relationship in reliability, with 60.12 mAh/10 min (72% piezoelectric) coming from walking on uneven surfaces with limited sun exposure.

This system can monitor ambient temperature/humidity (22.6C/58.8%) and will illuminate an emergency LED up to 10–12 hours, thereby expanding its use to hikers, field workers, and disaster responders. In the future, environmental sensors should be integrated into the main power distribution system and an automatic night light feature added.

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