

How Much Energy Can We Harvest Daily for Wearable Applications?

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Abstract—Emerging flexible and stretchable devices open up novel and attractive applications beyond traditional rigid wearable devices. Since the small and flexible form-factor severely limits the battery capacity, energy harvesting (EH) stands out as a critical enabler of new devices. Despite increasing interest in recent years, the capacity of wearable energy harvesting remains unknown. Prior work analyzes the power generated by a single and typically rigid transducer. This choice limits the EH potential and undermines physical flexibility. Moreover, current results do not translate to total harvested energy over a given period, which is crucial from a developer perspective. In contrast, this paper explores the daily energy harvesting potential of combining flexible light and motion energy harvesters. It first presents a multi-modal energy harvesting system design whose inputs are flexible photo-voltaic cells and piezoelectric patches. We measure the generated power under various light intensity and gait speeds. Finally, we construct daily energy harvesting patterns of 9593 users by integrating our measurements with the activity data from the American Time Use Survey. Our results show that the proposed system can harvest on average 0.6mAh @ 3.6V per day.

I. INTRODUCTION

The worldwide use of connected wearable devices has tripled in the last five years, and it is expected to exceed one billion by 2022 [1]. Wearable devices have many promising application areas ranging from health and activity monitoring to early diagnosis and prognosis [2]. Most notably, the emergence of physically flexible and stretchable devices opens up new form factors and use cases beyond rigid wrist-worn devices (e.g., electronic patches and devices embedded into clothes) [3]. However, the transformative potential of new wearable form-factors is severely challenged by bulky and rigid batteries. For example, a coin-cell battery attached to an electronic patch would undermine the innovative stretchable design. Emerging flexible batteries [4] alleviate this problem to some extent, but there is still a significant mismatch between the flexibility and size of the batteries and the devices. Even with significantly improved physical properties, relying on batteries degrades user satisfaction, thus, compliance due to recharging requirements. Hence, there is a strong need to find innovative techniques to power emerging stretchable and flexible wearable devices.

Energy harvesting has been widely accepted as a promising solution to eliminate or significantly reduce the dependency on batteries. Light EH is the most prominent approach since it can provide in the order of mWs in outdoor conditions [2].

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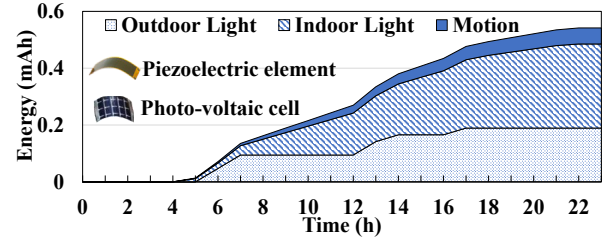


Fig. 1: A typical user with close to 0.6 mAh cumulative harvested energy over a day. Motion EH consists 10% of the total harvested energy. For reference, the Oura Ring 2 incorporates a 21 mAh @ 3.7 V battery, and advertises a battery life of 4-7 days.

The generated power quickly reduces to tens of μ Ws in indoor conditions, but it is still a significant amount when compared to other modalities. Other commonly used EH modalities include motion through piezoelectric materials and temperature difference through thermoelectric generator with 10 μ W and 1 μ W capacity, respectively [2]. To be practical for future wearable use, the EH solutions must match the physical properties of emerging designs such as electronic patches. Therefore, flexible photo-voltaic (PV) cells offer clear advantage with their superior performance, as shown in Figure 1. Similarly, flexible piezoelectric elements stand out for when the user is active, which is arguably the most interesting period for wearable applications. This paper considers these two modalities, since combining two complementary modalities can harvest more energy, as shown in Figure 1.

Given a set of EH modalities, there are two related fundamental research questions: 1) *How much power can wearable transducers generate under a specific condition?* 2) *How much energy can be harvested over a given period?* Existing energy harvesting studies typically focus on the first question and use a single modality [5, 6]. However, generated power is not sufficient to find the cumulative energy (e.g., the integral over a day) since the conditions change dynamically. Quantitative answers to these questions are key enablers for processor and memory subsystem designers, system-level designers, and application developers. Low-power designers can use the expected peak and average power output of energy harvesters to set a realistic target power consumption. System designers can use them to determine the available energy budget, which is required to design the power supply subsystem and other components. Finally, given a wearable device, application developers can use the energy harvesting budget to find the feasible duty ratio, i.e., the percentage of time the application

can stay active.

To answer the research questions in the previous paragraph, this paper explores the combined potential of wearable light and piezoelectric energy harvesters. We first design two subsystems optimized for light and motion energy harvesting modalities separately. This customization enables each circuit to operate at its own maximum power point (MPP). Then, these circuits are integrated to add their output current. This experimental setup is used to characterize the combined output power and the individual contributions under varying light intensity and gait speeds. We measure the performance in terms of the produced battery charging current and power. The output power cannot be used alone to estimate the total energy harvesting potential since it changes dynamically and sometimes even diminishes due to lighting and user activity variations. Hence, we extract the location and activity information of 9593 users from the *American Time Use Survey* (ATUS) dataset. The location data reveals the amount of time each person spends indoors and outdoors, while the activity data (e.g., exercise) helps us estimate the motion intensity. We combine the measured power with the extracted location and activity data to analyze the wearable energy harvesting potential of 9593 users.

As the major contributions, this work demonstrates:

- **Wearable light energy harvesters** can generate 511 μW and 144 μW under 1075 lux (outdoor) and 250 lux (indoor) of illuminance,
- **Wearable motion energy harvesters** can generate 7.9 to 15.5 μW as the gait velocity varies from 3 to 7 MPH,
- **Adding wearable motion EH modality to light EH** can increase the total harvested energy in a day by 10%,
- **Combining the power characterization with ATUS data** shows a median of 0.6 mAh @ 3.6 V daily energy harvesting potential, which can be utilized to run low-power wearable devices.

II. RELATED WORK

A growing number of recent studies employ flexible PV-cells for wearable light energy harvesting [5–8]. The generated power is a function of the PV-cell area and light intensity. In addition, the output power depends on the placement of the PV-cell since the radiation on the surface is proportional to the sine of the incident angle. Table I confirms that the generated power grows with light intensity and area.

Wearable piezoelectric energy harvesting solutions in the literature typically use bulky mechanical designs to maximize power output [9]. Hence, they are not suitable for physically flexible wearable devices. In contrast, we place flexible piezoelectric elements directly on the joints, using joint motion as the energy source. A few recent studies investigated this energy harvesting modality, enabled by flexible piezoelectric materials such as Polyvinylidene Fluoride (PVDF) and Macro-Fiber Composite (MFC). One such study demonstrates 6.2 μW of maximum generated power from walking motion with a PZT based piezoelectric patch transducer placed on the front of the knee [10]. A similar study places PVDF beams on the

TABLE I: Wearable Energy Harvesting Studies.

Ref.	Modality	Size	Source	Power
[5]	Light	813 mm ²	500 lux	155 μW
[6]		4320 mm ²	320 lux	77 μW
[7]		487 mm ²	500 lux	69 μW
[8]		768 mm ²	2000 lux	210 μW
[10]	Motion	2135 mm ²	Walk/Run	6.2/12 μW
[11]		2964 mm ²	Walk/Jog	1.9/3.7 μW
[12]		2380 mm ²	1.5 Hz	0.9 μW
This Work	Light + Motion	4672 mm² 2380 mm²	250/1075 lux 3/5/7 MPH	31 – 526 μW

knee using a bodysuit and reports 1.9 μW during walking and 3.7 μW during jogging [11]. Another study reports 0.9 μW harvested power from a knee harvester during the walking motion with an MFC8528P2 piezoelectric element [12]. These prior studies provide the power values directly at the output of the harvester. Therefore, they do not account for the losses due to rectification, leakage, impedance mismatch, and regulation. *In strong contrast, our study measures the current flowing into the battery after all such losses.*

Combining multiple energy harvesting modalities has attracted attention in the last decade due to its more stable and sufficient power availability over single modality approaches [13, 14]. Numerous circuit topologies have been proposed for combining multiple sources [15]. These studies focus on industrial and environmental use cases, ignoring the form-factor and low-power limitations in a wearable ecosystem. For example, the work in [14] assumes high vibration frequencies for the piezoelectric motion energy harvester. Similarly, the authors in [16] use large and inflexible PV-cells for light energy harvesting. A recent study focuses on combining piezoelectric and electromagnetic wearable energy harvesting modalities [17]. However, it uses bulky magnets that undermine the benefit of reducing battery-size.

This paper is the *first to combine physically flexible light and piezoelectric energy harvesting* to the best of our knowledge. Furthermore, we estimate the *daily energy harvesting potential with user activity statistics*, unlike prior work that only reports the generated power. We will release our datasets to the public to enable reproducibility and further studies.

III. MULTI-MODAL ENERGY HARVESTING SYSTEM

We use two distinct subsystems for light and motion EH modalities, as shown in Figure 2. This setup allows for having control over operating at the maximum power point for each modality separately. This section presents the operation principles of each energy harvesting system and their combination.

A. Motion EH Subsystem

Motion energy harvesters convert mechanical energy into electrical energy. The transducers in this work are flexible piezoelectric elements placed on the knee. We target the knee joint as previous studies on wearable motion EH showed that the biomechanical energy potential at the knees are higher than other joints [18]. Besides, knees follow a periodic trajectory, which allows continuous harvesting of energy while walking. We record the knee angle during different gait speeds with a

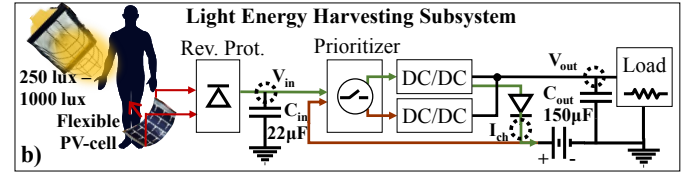
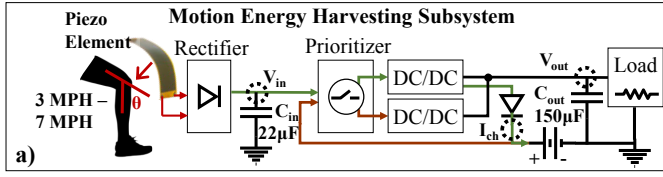


Fig. 2: a) Motion Energy Harvesting Subsystem b) Light Energy Harvesting Subsystem.

flexible angle measurement sensor placed at the knee [19]. A robot frame then mimics the knee-bending motion to obtain reproducible results, while the flexible piezoelectric element(s) on the robot frame generate energy.

Figure 2a illustrates the main components and the operation principle of the motion EH subsystem. The charge generated by the piezoelectric element is rectified and stored on an input capacitance. Once the voltage reaches a programmable upper threshold, a prioritizer module transfers the accumulated charge to an output capacitance through a buck converter. When the voltage on the input capacitance decreases below a lower threshold during the transfer, the buck converter is disabled. Then, the harvested energy starts accumulating again on the input capacitance. This process repeats until a regulated voltage at the output is obtained, as shown in Figure 3. The lower and upper thresholds are set to 5 V and 6 V respectively, as depicted in Figure 3a. While the output voltage is regulated, the harvested energy is transferred to the battery, as shown in Figure 3c. If the output regulation cannot be maintained by harvested energy, the prioritizer regulates the output using a backup battery through another buck converter.

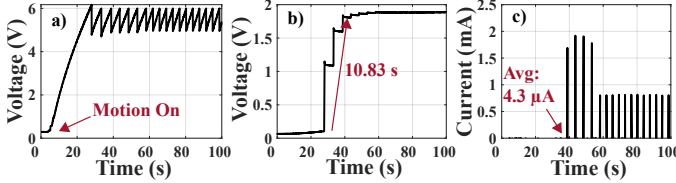


Fig. 3: 3 piezoelectric elements in series at 7 MPH gait speed. a) V_{in} b) V_{out} c) I_{ch}

B. Light EH Subsystem

Light energy harvesters use PV-cells to transduce the light energy into usable electrical energy. In this work, the energy source is a flexible PV-cell placed on the leg. We choose the leg as the target location since the motion EH subsystem targets the knee joint as explained in the previous section. Otherwise, combining the two systems would be unrealistic due to excessive wiring overhead and clothing limitations.

The operation principles of the light EH subsystem shown in Figure 2b is the same with the motion EH subsystem. Figure 4 depicts the typical behavior of this subsystem under 250 lux illuminance with two PV-cells in series. In this case, the lower and upper thresholds are set to 4 V and 5 V, respectively.

C. Combined Energy Harvesting System

Multiple transducers and EH modalities can be combined using different topologies. One extreme option is to rectify and regulate the voltage produced by each transducer separately,

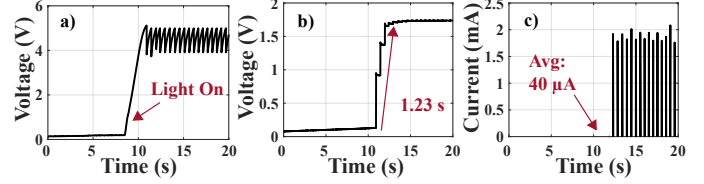


Fig. 4: 2 PV-cells in series at 250 lux. a) V_{in} b) V_{out} c) I_{ch}

and then add them up. Although this is the most straightforward approach, it incurs extra losses due to additional rectifiers and regulators. At the other extreme, the harvested voltage from all transducers can be first superimposed before rectifying and regulating them altogether. This approach uses one rectifier and one regulator, but the voltages may add up destructively due to synchronization issues.

In this work, we superimpose the AC voltages generated by the piezoelectric elements and rectify/regulate the superimposed voltage using the subsystem shown in Figure 2a. The same approach is applied to the superimposed DC voltage generated by the PV-cells with the subsystem shown in Figure 2b. Finally, we combine the two subsystems through diode OR-ing, as shown in Figure 5. In this configuration, the regulated output at the output of both subsystems connect to a large capacitance. This approach enables each subsystem to operate at its MPP. In addition, the subsystems are connected to the same battery. This way, both subsystems start charging the battery once the system achieves regulated output.

The programmable upper and lower thresholds are critical factors for the energy harvesting performance, as they control the operation at the maximum power point of the corresponding modality. Therefore, we explain the factors specific to each modality that play an important role in choosing these thresholds in the following.

Using multiple PV-cells: Small form-factor flexible PV-cells typically generate less than 3V at their terminals. Moreover, the generated DC voltage passes through a reverse protection diode before it accumulates on the input capacitance, causing a further voltage drop. If this voltage does not exceed the prioritizer's minimum upper threshold, the produced charge cannot be transferred to the output. Hence, the output voltage

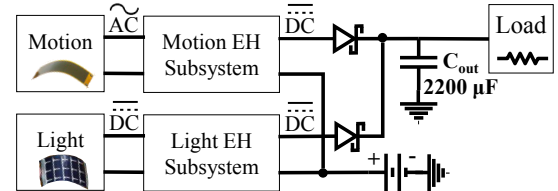


Fig. 5: The topology for combining the motion and light energy harvesting subsystems.

cannot be regulated. Multiple PV-cells could be connected in series to boost the voltage accumulated on the input capacitor to avoid this problem. Series connection shifts the maximum power point to higher voltages, as shown in Figure 6.

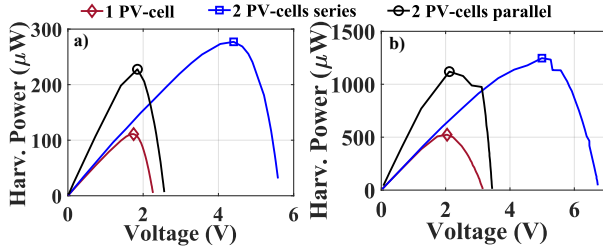


Fig. 6: MPPs for PV-cells under a) 250 lux b) 1075 lux.

Using multiple piezoelectric elements: Piezoelectric materials generate a large potential difference between their terminals, typically in the order of 10 V_{pp}. The generated AC voltage passes through a full-wave rectifier, and the obtained DC voltage accumulates on the input capacitance. However, they provide little current as their impedance is in the order of 100 kΩs. To this end, using multiple elements in a stack is a promising solution, as stacking does not incur any space overhead as long as it does not cause discomfort to the user. Moreover, having the elements in a stack minimizes the concerns due to voltage synchronization.

The maximum power point of a piezoelectric element happens at half of the open circuit rectified voltage [20]. Since the voltage generated by the piezoelectric elements is not a pure sinusoid due to knee dynamics during walking, calculating the rectified DC voltage is not straightforward. For this reason, we experimentally measure the rectified voltages for different gait speeds. Figure 7 illustrates the voltage on the input capacitor after rectification with a single element as well as series and parallel configurations of three elements. In all gait speeds, single and parallel configurations result in approximately 4 V on the capacitor. Similar to the light EH case, this voltage may not exceed the prioritizer’s minimum upper threshold. In contrast, the series configuration obtains higher rectified voltages. Therefore, we set the upper and lower thresholds according to the obtained voltages with the series configuration to operate at the MPP. For example, for the 3 MPH case in Figure 7a, the motion EH subsystem is configured to maintain the voltage on the input capacitor at about $\frac{10}{2} = 5$ V.

IV. EXPLORATION OF THE WEARABLE EH POTENTIAL

This section first presents the implementation of the EH systems and the experimental procedure for measuring their performance. Then, it reports the battery charging current measurements for each harvester. Finally, it combines these measurements with the ATUS dataset and summarizes the energy harvesting potential for 9593 users.

A. Experimental Setup and Procedure

Experimental Setup: We implement the motion and light energy harvesting subsystems with two LTC3331 power management ICs by Linear Technology [21]. LTC3331 consists of a low-loss full-wave bridge rectifier and a buck DC/DC

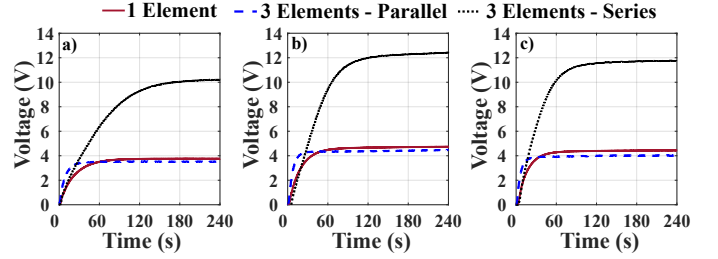


Fig. 7: Rectified DC voltages. a) 3 MPH b) 5 MPH c) 7 MPH

converter for harvesting energy from PV-cells and piezoelectric sources. It also incorporates a battery charger for when excess harvested energy is available. A programmable undervoltage-lockout hysteresis window controls LTC3331’s operation at the maximum power point. For example, the smallest window configuration turns on the buck converter when the voltage on the input capacitor reaches 4 V and turns it off when the voltage goes down to 3 V. We set these windows according to the maximum power points extracted from Figures 6 and 7, as listed in Table II.

The subsystems connect to a common 3.6 V lithium-ion rechargeable battery, such that each LTC3331 charges the battery with its own harvested energy. For this, the “BAT_IN” pins of LTC3331s are tied to the +ve terminal of the battery. This way, each LTC3331 controls the charge on its input capacitance and sends the excess charge into the battery after the output is in regulation.

Experimental Procedure: In the motion energy harvesting subsystem, the energy source is flexible and small form-factor (2380 mm²) MFC8528P2 piezoelectric elements [22] placed on the robot frame. The robot frame mimics the knee bending motion according to the knee angle recordings taken while walking (3 MPH), fast walking (5 MPH), and running (7 MPH). We demonstrate the capacity of the motion EH subsystem with i) one piezoelectric element, ii) three stacked piezoelectric elements connected in series.

In the light energy harvesting subsystem, the energy source is flexible and small form-factor (2336 mm²) PowerFilmSolar SP3-37 PV-cells [23]. The PV-cells are placed on a cylindrical frame with a 3 cm radius of curvature to imitate placement on the leg. We measure the generated current by the light EH subsystem in indoor office (250 lux) and outdoor conditions (1075 lux), as specified in [24]. For office conditions, we place the cylindrical frame on a desk that receives an illuminance of 250 lux in a typical laboratory setting. In a realistic scenario, the PV-cells do not always face the light source. To account for this, we measured the current when the PV-

TABLE II: Light and Motion EH subsystem hysteresis window configurations to operate at the MPP of each configuration.

	Light EH		Motion EH	
	1 PV-Cell	2 PV-Cells Series	1 Element	3 Elements Series
250 lux	3-4 V	4-5 V	3 MPH	3-4 V
1075 lux	3-4 V	5-6 V	5 MPH	5-6 V
			7 MPH	5-6 V

cells are turned *towards* and *away* from the light source. For outdoor conditions, we place a 500 W halogen work light with adjustable light intensity directly across the PV-cells. Then, we adjust the light intensity to read 1075 lux on a commercial lux-meter at the level of the PV-cells. We demonstrate the capacity of the light energy harvester subsystem with i) one PV-cell, ii) two PV-cells connected in series.

In the following, we measure the current flowing into the battery when the load is an open circuit for all different light and gait configurations. Since the load is open, the harvested energy is used to charge the battery as soon as the output is regulated at 1.8 V. Finally, we combine the measurements with the ATUS dataset to explore energy harvesting potentials of 9593 users over one day.

B. Motion and Light EH Measurements

The hysteresis window of the LTC3331 in the motion EH subsystem is configured according to Table II depending on the gait speed and configuration of the piezoelectric elements. The output cannot be regulated at 1.8 V with a single element at 3 MPH, as shown in Table III. Moreover, the charge transfer cannot be initiated at all due to not enough voltage on the input capacitor, which results in zero battery charging current. For 5 MPH and 7 MPH, the average battery charging current is in the vicinity of 1 μ A. With three stacked piezoelectric elements in series, the output can be regulated at 1.8 V for all three gait speeds, as illustrated in Figure 3 for 7 MPH. For 3 MPH, the average battery charging current is 2.2 μ A, while for 5 and 7 MPH it is 4 and 4.3 μ A, respectively.

TABLE III: Motion EH subsystem measurements.

	1 Element	3 Elements Series
3 MPH	0 μ A, 0 μ W	2.2 μ A, 7.9 μ W
5 MPH	1.4 μ A, 5 μ W	4.0 μ A, 14.4 μ W
7 MPH	0.7 μ A, 2.5 μ W	4.3 μ A, 15.5 μ W

The hysteresis window of the LTC3331 in the light subsystem is configured according to Table II depending on the illumination and PV-cell configuration. The output cannot be regulated by energy harvesting alone with one PV-cell regardless of the illuminance, as shown in Table IV. When two PV-cells are used in series, the output can be regulated at 1.8 V under 250 lux, as depicted in Figure 4. When the PV-cells are turned away from the light source, the battery is charged with 6.8 μ A average current. When they face the light source, the average charging current increases to 40 μ A. Finally, the average charging current is 142 μ A under 1075 lux, which is significantly more than any other configuration.

TABLE IV: Light EH subsystem measurements.

	1 PV-Cell	2 PV-Cells Series
250 lux (away)	0 μ A, 0 μ W	6.8 μ A, 24.5 μ W
250 lux (towards)	0 μ A, 0 μ W	40 μ A, 144 μ W
1075 lux	0 μ A, 0 μ W	142 μ A, 511 μ W

C. Combined EH System Measurements

The combined system uses two PV-cells and three piezoelectric elements in stack, since the performance of the subsys-

tems with one PV-cell and one piezoelectric element are poor. We evaluate the performance of the systems at all six different combinations of light and gait speed conditions (i.e. 250 lux - 3 MPH to 1075 lux - 7 MPH), as shown in Table V. According to our measurements, the combined system successfully adds up the battery charging currents of the individual subsystems. For example, under an illuminance of 1075 lux and a speed of 5 MPH, the light and motion EH subsystems harvest 142 μ A and 4 μ A, respectively. The combined EH system harvests 146 μ A under the same conditions. This potential can be used to power a variety of sensors and low-power components, as listed in [15].

TABLE V: Combined EH system measurements.

Light (lux) ↓	3 MPH	Speed 5 MPH	7 MPH
250 (away)	8.5 μ A, 31 μ W	11 μ A, 40 μ W	11 μ A, 40 μ W
250 (towards)	42 μ A, 151 μ W	44 μ A, 158 μ W	44 μ A, 158 μ W
1075 (outdoor)	144 μ A, 518 μ W	146 μ A, 526 μ W	146 μ A, 526 μ W

D. Energy Estimation over a Day

The final step of the exploration is to estimate the total energy harvesting potential over a given time duration using the measurements throughout this work. This process is not simply the *duration* multiplied by *power*, as the harvested power varies due to the dynamic behavior of lighting and user activity. To this end, we use the ATUS dataset and obtain realistic EH potentials for various users in this dataset.

ATUS dataset consists of the distribution of different activities for various persons on a typical day in their lives [25]. Specifically, the dataset contains daily distributions of 18 different activity categories, such as sleeping, working, or exercising, for 9593 users. We use this dataset to obtain the daily energy harvesting potential of all the 9593 users. For this, we first obtain the activity and location information for each user from the dataset. The activity information is required to estimate the amount of energy harvesting from the knee bending motion. We assign each activity a gait speed from the set of {0, 3, 5, 7} MPH. For example, sleeping is assigned 0 whereas exercising is assigned 7 MPH. Similarly, the location information is necessary to estimate the energy harvesting from light as the indoor/outdoor conditions significantly affect the EH potential. We assign the average of 250 lux measurements to office conditions, half of it to home conditions and three times of it to store/shopping conditions, while 1075 lux measurements correspond to outdoor conditions. In this way, we convert the current measurements into realistic energy harvesting patterns.

Figure 8a shows the EH pattern for a typical user in the dataset. This particular user is asleep between 11PM-5AM, where no energy is harvested at all. During the day, the user spends time outdoors (6AM, 7AM and 13PM and 14PM) where the energy harvested due to outdoor light is dominant. The energy harvested by the motion EH subsystem accounts for 10% of the total energy harvested in the day. A more detailed breakdown for this user is given in Figure 1. Figure 8b shows the cumulative harvested energy for the users

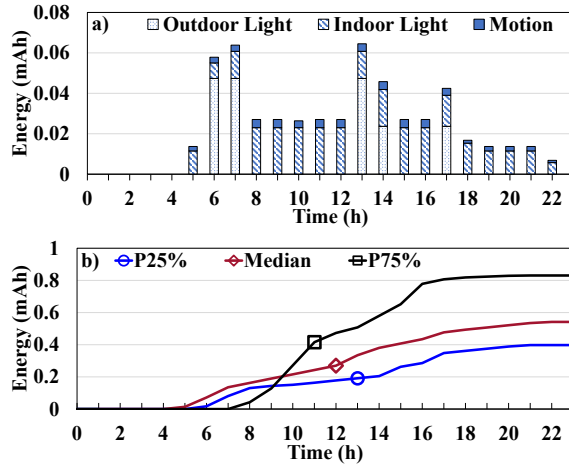


Fig. 8: a) Median hourly EH distribution of 9593 users b) Cumulative EH for the 25th, 50th and 75th percentile.

that correspond to the 25th, 50th (median) and 75th percentile among all users, respectively. The median curve suggests that for the majority of users, close to 0.6 mAh @ 3.6 V can be harvested in a day with a typical wearable combined light and motion energy harvester such as the one used in this work. We emphasize that the values we plug in can be changed with other measurements in the literature to extend the methodology to other energy harvesting modalities and techniques.

V. CONCLUSIONS, LIMITATIONS & FUTURE DIRECTIONS

Novel flexible and stretchable wearable devices require energy sources that match their physical properties. These physical constraints severely limit the use of batteries and their capacity. We argue that wearable energy harvesters can satisfy the energy need as orthogonal sources to batteries. However, the energy harvesting potential of wearable harvesters remains unknown despite their potential. To this end, this work explores the potential of a combined wearable light and motion energy harvester using the location and activity statistics of 9593 users. Our results show that the proposed system can harvest 0.6 mAh @ 3.6 V over a day.

The power measurements in this work are performed at the MPP since we set the hysteresis windows based on the input configurations. However, in practice, operating at the MPP relies on distinct MPP tracking methods for motion and light EH. Similarly, light energy harvesting could be lower in practice due to shading, dirt, or scratches on the PV-cells. Finally, this work considers motion EH due to bending motion only. In actual use cases, other forces such as friction and twisting could increase the harvested energy. We will open-source our datasets and models to facilitate future research and address these uncertainties. More diverse EH data can help the research community accurately characterize the wearable energy harvesting potential. We also plan to build a wearable prototype and use it to log the battery charging currents during extended daily use as part of our future work.

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