Demo: Hardware to unleash novel energy sources for outdoor sensor networks

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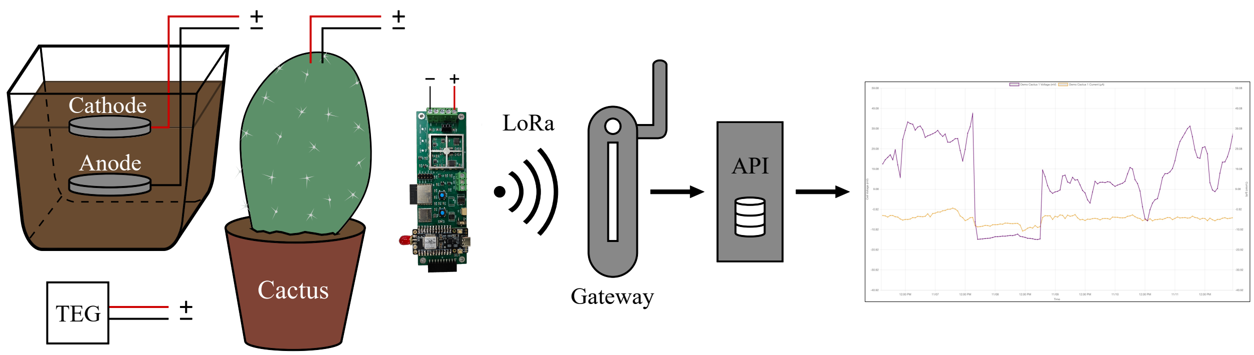

Figure 1: Demo setup: three low-power energy sources (soil-based microbial fuel cell, prickly pear cactus, and thermoelectric generator) are each connected to our Environmentally NeTworked Sensor (ENTS) node. Data is uploaded via LoRaWAN or WiFi to our data visualization website where live data is displayed for the users.

Abstract

We present a demonstration of a wireless sensor network system to measure power output from nontraditional low-power energy sources. Our system has the necessary measurement fidelity for logging power traces and environmental data to a web based measurement portal and facilitates transition from in-lab experiments to the field. Our demonstration shows different use cases of our system by logging various energy sources: a soil-based microbial fuel cell, a prickly pear cactus, and a thermoelectric generator. A large screen will be used to continuously display live data traces.

CCS Concepts

• **Hardware** → **Sensor applications and deployments**; **Sensor devices and platforms**; **Wireless integrated network sensors**; **Renewable energy**.

Keywords

Wireless Sensor Networks, Renewable Energy Sources, Data Visualization, Microbial Fuel Cell, Sustainable, Scalable, Field Sensing

1 Introduction

Wireless Sensor Networks (WSNs) are widely used in ecological monitoring and agricultural sensing, enabling real-time data collection for applications such as climate change tracking, soil health assessment, and precision farming. These networks often rely on solar energy coupled with Li-Ion batteries [8]. However, solar energy is not a universally reliable solution. Furthermore, both batteries and solar panels require high-impact minerals like tin and cobalt that can leach into the soil and/or generate harmful electronic waste, raising sustainability concerns [7]. To address these challenges, there is growing interest in alternative low-power energy sources with smaller environmental footprints, such as soil-based microbial fuel cells (SMFCs), prickly pear cacti, and thermoelectric generators (TEGs). The widespread adoption of these alternative energy sources in low-power electronics remains limited, however, due to their highly variable and environmentally sensitive power outputs. For sensors to operate reliably in such dynamic conditions, a deeper understanding of these fluctuations is essential. This understanding hinges on extensive data collection, which, in turn, requires specialized tools capable of accurately capturing ultra-low-power outputs in real-world environake sureents. With a robust dataset, machine learning techniques can be employed to optimize computing algorithms and extend sensor longevity, ultimately enhancing the viability of these alternative energy sources [1, 2].

To address the challenges of monitoring and characterizing low-power energy sources, we introduce the Environmentally NeTworked Sensor (ENTS) platform, a real-time, field-deployable system for cost-effective monitoring and characterization of low-power energy sources. ENTS features ultra-low-power measurement capabilities, high-resolution power logging, and remote monitoring, enabling long-term scalable field deployments. It also supports environmental sensor integration to correlate power generation with factors such as temperature, moisture, and microbial activity. Our demo showcases ENTS monitoring multiple unusual sources of energy in real-time, highlighting its ability to track and visualize energy fluctuations and auxiliary data at high granularity.

2 Background

Many emerging low-power energy sources interact in complex ways with their surrounding environment, and as a result they are difficult to model. Below we describe some example energy sources that we plan to incorporate in our demo and provide background on their mechanisms.

Soil-based Microbial Fuel Cells. SMFCs rely on naturally occurring exoelectrogenic bacteria metabolizing organic matter in the soil to generate a flow of electrons through a connected load. Each

SMFC consists two electrodes made of a conductive non-corrosive material, typically carbon felt. The anode placed beneath the soil in an anerobic environment, and the cathode has once face exposed to the surface in an aerobic environment. SMFCs power output can vary drastically based on environmental conditions. Under ideal lab conditions, a single SMFC produces 100 µW of power, while a limited field study showed power production of 0.5 µW to 2 µW [6]. Far more data is needed to reliably characterize SMFC behavior in the field, as many essential variables like soil drainage, seasonal weather patterns, rhizome interactions, and more, are difficult or impossible to replicate in laboratory settings.

Prickly Pear Cacti. Power is harvested from prickly pear cacti through crassulacean acid metabolism (CAM) photosynthesis, a process unique to plants in arid climates. CO2 from the atmosphere is stored as malic acid during the night to prevent water loss and is consumed during photosynthesis in the day. The presence of conductive metals on the surface of cacti allows electrons to flow from the sun-facing side (positive) to the shaded side (negative) to generate power. The energy density for CAM plants is $9.4\,\mathrm{mW\,h\,m^{-2}}$, which is sufficient to power a WSN node [5]. The natural adaptations of cacti to arid environments make them suitable for powering WSNs in remote locations.

Thermoelectric Generators (TEG). TEGs use the Seebeck effect to convert a temperature gradient to electrical energy. TEGs are solid state semiconductor devices making them a robust form of power generation. In agricultural environments, TEGs have been able to produce 100 µW to 320 µW of power from the temperature difference between ambient air and surface level soil [3]. The power harvested is able to power WSN for soil monitoring and additional ecological monitoring applications. This energy source is well understood, but we include it because TEGs are highly responsive, which will allow for an ineractive aspect to our demo.

3 System Design

One key design consideration behind ENTS is enabling study of low-power energy sources where the transition from in-lab to field experiments is necessary [4]. The ENTS platform consists of sensing hardware, the *node*, and a web portal for centralized data storage and visualization, the *backend*. The *node* is responsible for accurately measuring voltage and current traces, reading externally connected environmental sensors, and sending reliable wireless messages without data loss. The platform supports WiFi due to the ubiquitous availability in laboratory settings and the relative lack of power constraints. After transitioning to the field, data are uploaded via LoRaWAN to increase range and reduce power consumption while powered by batteries. The *node* is about the size of a smartphone and costs 50 USD per device. The voltage and current have an accuracy of 16.21 µV and 700.21 nA with ranges of −2.2 V to 2.2 V and −0.9 mA to 0.9 mA. The *backend* supplies an HTTP API interface to permanently store sensor measurements and plots to visualize historical and live data transmitted from sensors.

4 Demo Setup

We will connect an ENTS node to three different renewable energy sources: an SFMC, a TEG and a prickly pear cactus. The SMFC and cactus show the system monitoring novel energy systems that our lab is actively researching, while the TEG offers a more responsive and interactive experience. The SMFC and cactus will have relatively stable energy output during the demo session, while the TEG will be highly responsive to user interaction. Users will be able to touch their finger or use a heat gun with the TEG to generate power and observe real-time changes on the website displayed by a nearby laptop. For all energy sources, voltage and current measurements will be transmitted either through venue WiFi or a LoRaWAN gateway that we bring. An overview of the demo setup is shown in Fig. 1. In addition to live data, the website also makes historical data from our ongoing research accessible, which will let users see how SMFC and cactus energy output behave over longer timescales.

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