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Design of a clean energy portable generator for remote IoT applications

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Design of a clean energy portable generator for remote IoT applications

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Abstract

This article presents a conceptual design proposal for a micro-scale energy generation system based on the bacterium *Geobacter sulfurreducens* (GS), which can provide electricity. It is intended for use in remote locations or emergencies where conventional power sources are unavailable. The design is guided by three core principles: clarity, simplicity, and uniqueness based on the Design Thinking Methodology. The concept draws inspiration from Microbial Fuel Cells (MFCs), providing an environmentally friendly, low-maintenance solution for decentralized power generation. The conceptual proposal encompasses basic mechanical considerations; and the high level electrical circuit, which comprises a booster, a microcontroller, multiple sensors for data acquisition, and a LoRa communication module; marking the initial step toward integrating bacterial electricity generation into product design for sustainable, low-power solutions tailored to remote and challenging environments.

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Keywords:Geobacter Sulfurreducens, conceptual proposal, clean energy generator, portable microgenerator.

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1. Introduction

In the search for energy-efficient gadgets that can operate in extreme conditions, we find the use of small generators incorporated into those gadgets. There are various established methods for generating electricity, ranging from solar and wind power to hydroelectric systems. However, a significant gap remains in producing electricity in extreme and

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unconventional environments where traditional methods are not viable. For example, solar energy can be practical in locations where sunlight is abundant and efficiently converted with a well-developed infrastructure. Similarly, hydroelectric dams and wind turbines can be used near rivers to harness kinetic energy and convert it into electricity. Yet, challenges arise in scenarios such as minery, inside caves or within wastewater systems where monitoring pressure, temperature, flow rates or other variables need to be measured with the design of small gadgets that can be energized and used for constantly acquiring data of these systems and where conventional energy solutions fall short, highlighting the need of alternative methods of power generation.

Therefore, given the need for innovative solutions in this exploratory phase of development, this paper presents a conceptual proposal for utilizing low-rate consumption energy sensors in an IoT scenario with remote sensing and data acquisition, leveraging the bacterium *Geobacter sulfurreducens* (GS). As it has been proved and tested with in-lab experiments on how this organism produces electricity, this project explores the usage of the technology for creating small energized gadgets and systems. While promising, this project requires further exploration to determine the viability of the solution and identify manufacturing opportunities- an endeavor that aligns with current research directions in smart, bio-integrated systems.

The paper is structured to support this exploratory approach: the first section presents a comprehensive literature review providing essential background information on the bacteria and its bio-electrochemical properties. The second section details the methodology and conceptual proposal, including comprehensive tables of the components and their respective consumption rates for each device. Finally, the conclusions, discussion and future work section outlines pathways to continue exploration in this research area, with particular focus on how findings could improve product design for energy-autonomous devices.

2. State of the Art: How bacteria can create electricity

Microbial Fuel Cells (MFCs) offer an innovative approach to bioelectric energy generation by utilizing the natural abilities of microorganisms. In one example, a microbial fuel cell is designed with electronically connected anode, cathode, and reference electrodes, featuring two key biocatalysts in the anode chamber: Cellulomonas uda ATCC 21399, which hydrolyzes and ferments biomass into fermentable sugars derived from both hexose and pentose sugars, and *Geobacter sulfurreducens*, an alcohol-tolerant electrogene capable of transferring electrons from fermentation products to the anode, thereby generating electricity. This system facilitates the direct bioelectric conversion of complex biomass under mild, mesophilic conditions, offering a promising strategy for renewable energy production [1].

Building on this, in a related study, Serment [2] explored the identification and isolation of exoelectrogenic microorganisms from the Lerma River (State of Mexico) where sediments and wastewater treatment plant sludge were explored using MFCs as the primary tool for microbial identification and characterization. Among the isolated species, *Clostridium sordellii* and *Clostridium bifermentans* were found to be less efficient compared to *Geobacter sulfurreducens*. However, these bacteria demonstrated potential for in situ electricity generation in polluted environments, offering promising application for bioremediation and environment clean-up. Similarly, Fakhirruddin [3] assessed power outputs from MFCs using exoelectrogenic bacteria isolated from rice paddy field soil. Both mixed microbial consortia and pure isolates showed significant power generation, with mixed cultures yielding higher outputs, indicating the importance of microbial interactions in optimizing electricity generation.

Materials play a crucial role in Microbial Fuel Cells, and significant advances have been achieved in improving MFC efficiency through innovative material developments. Cheng [4] synthesized iron-doped carbon and nitrogen (Fe@CN) nanomaterials to modify the surface of carbon paper anodes in MFCs. This modification led to an increase in electrochemical surface area, promoting enhanced microbial adhesion and facilitating efficient extracellular electron transfer (EET). As a result, the modified MFC achieved a peak voltage of 792.76 mV and

demonstrated stable electrical output over 300 hours, highlighting the potential of nanomaterial-based strategies for improving MFC performance in practical applications.

Building on the concept of MFCs as a renewable energy source, Kunz [5] presented a dual-function system comprising both MFCs and microbial batteries powers by *Geobacter sulfurreducens* and *Clostridium pasteurianum*. This integrated approach utilizes the same microbial processes and electrode configuration to simultaneously generate and store electricity, offering a promising pathway for sustainable energy solutions. The use of organic waste or other renewable biomass as an energy source within these systems underscores the potential for microbial technology to contribute to environmentally friendly and renewable applications.

Another notable innovation in the MFC technology is the coupling of MFCs with constructed wetlands (CW-MFCs) to harness plant root exudates as an additional energy source. Guadarrama [6] investigated this integration using *Geobacter sulfurreducens* DL-1 as the catalyst in CW-MFC systems fed with organic compounds from plant species such as *Juncus effusus* and *Philodendron cordatum*. The study found that plant exudates, particularly from the first type mentioned, significantly boosted power generation, with peak outputs of 107 mW/m^2. This result suggests that optimizing the delivery of root compounds to the microbial biofilm could escalate the performance and sustainability of CW-MFC systems, thereby advancing their viability.

In the quest to further strengthen the efficiency of MFCs, Ren [7] developed a novel three-dimensional microporous graphene scaffold to improve the performance of MFC anodes. The three-dimensional graphene structure addresses several common limitations in MFCs, such as poor electron transfer and inadequate nutrient delivery to microbial biofilms. By augmenting conductivity, increasing surface area, and supporting the growth of dense biofilms, this innovation led to a record power density of over 10,000 W/m^3, demonstrating a significant leap in the compactness and sustainability of MFCs.

Finally, Howley [8] provided critical insights into the mechanisms underpinning electron transfer in *Geobacter sulfurreducens*, specifically the formation of Intracytoplasmic Membranes (ICMs). These ICMs facilitate the efficient transfer of electrons across the bacterial outer membrane, a crucial feature for energy production under energy-limited conditions. The continuous connection between the ICMs and the periplasmic space enables efficient electron transport, which is essential for both respiration and energy conservation. This discovery not only bring us closer to the understanding of the microbial processes involved in MFCs but also opens new avenues for optimizing microbial performance and improving MFC efficiency.

In summary, recent advancements in microbial fuel cell technology have propelled this field closer to practical and sustainable energy solutions. Continued research in the topic, particularly in microbial interactions, material science, and novel bioreactor designs, holds the potential to unlock the full capabilities of MFCs in renewable energy generation and environmental remediation.

3. Creating products from in-lab studies

Literature review showcased the process that lies within the use of fuel bacteria, the operation voltage, and the autonomy of the MFC. Contribution from this paper relies on the design proposal for applying this type of electricity generation into products that could benefit from its usage in extreme scenarios such as mining or polluted water environments where electric generation is a challenge. This work is the beginning of the search study where a system is proposed by implementing this technology for energizing low-consumption components for data acquisition using accessible components and pieces. The subsequent phases of this research will focus on prototype construction and empirical testing to establish the system's practical viability.

Key insights from the literature review supported the evaluation of this proposal's feasibility and are mentioned next.

Cheng [4] works on a short-term performance evaluation (e.g., 300 h), making a future challenge the long-term reliability for a real-world application. The article focus is regarding the usage of a single type of anode modification

(Fe@CN), which limits the possible use of different materials or combinations that might perform better regarding electron transfer.

Kunz [5] underscores the importance of conducting further research to develop a functional prototype in future work. As key insights, Kunz highlighted that the growth of *Geobacter sulfurreducens* and *Clostridium Pasteurianum* depends on precise environmental factors such as pH, temperature and nutrient availability. Due to these constraints, the proposal introduces a 'micro-system' designed to maintain optimal conditions, ensuring a viable and consistent energy source.

For Guadarrama [6] the scalability of bacterial use in practical applications is not addressed. Since the study was conducted in a controlled bioreactor setup, the laboratory performance observed may differ from the outcomes expected in the context of our proposed application. This research also has a dependency on specific substrates, *Juncus Effusus* and *Philodendron Cordatum* root exudates, which limits its applicability in scenarios where these plants are present. Another key challenge, particularly relevant to our proposal, is the short-term performance, while long-term performance has yet to be evaluated.

Ren [7] noted that the effective operation of GS requires an oxygen-free environment, as the bacteria is anaerobic. This presents a significant challenge for miniaturized devices and limits its practical applicability. Furthermore, the study reports that the energy generated corresponds to only 3.1% of the predicted maximum current density for this microbe.

According to Howley [8], understanding the formation of ICMs in the presence of GS may provide insights into the metabolic strategies employed by bacteria in biofilms under energy-limited conditions.

Building on these findings, this article explores the application of the bacteria in a real-world scenario, where environmental conditions are not fully controllable. By adopting an iterative methodology for testing and experimentation, the study aims to identify limitations, challenges and potential drawbacks of the proposal, contributing to the development and refinement of the proposed system. As a result, the Design Thinking methodology was implemented for further development of the concept.

4. **Design Thinking Methodology**.

This paper employed the design thinking methodology, following the iterative and non-linear stages of Empathize, Define, Ideate, Prototype, and Test [9]. Implementing design thinking at the project's inception is beneficial as it ensures solutions are technologically feasible, economically viable and relevant to user needs [10]. The iterative methodology enabled the design team to continously refine and reevaluate concepts through several iterations based on results and findings from each stage, with these principles providing a decision-making framework.

This project adopted three core principles: Clarity, Simplicity and Harmony. These principles served as guidelines that facilitate each design stage, ensuring consistency and focus throughout the process, as the design team focused on its functionality, viability and realiability of the design proposal. The three principles are explained next.

- **Clarity** - Documentation and stage tracking were two key considerations aligned with this principle, implemented to support future work and proposal refinement. This principle ensures that all project phases remain transparent and well-documented for continued development or pivoting.

- **Simplicity** – This principle seeked to identify proposals where manufacturing and implementation are feasible. It also guided the team toward practical solutions that can be produced and deployed within existing constraints and capabilities.

- **Harmony** – This principle is considered once prototyping and testing results provided insights into the proposal. It helps to define detailed design specifications needed to integrate both mechanical and electrical systems into a cohesive solution.

This paper adresses the first two principles – Simplicity and Clarity – through the Emphatize, Define and Ideate stages; focusing on developing an initial conceptual proposal. The Harmony principle is addressed through the Prototype and Test stages, which encompass electrical prototyping, testing and insights analysis. Insights enable the design team to make informed decisions: either advancing to detailed mechanical design – materials and manufacturing processes – or pivoting to refine the conceptual approach.

The following table explains the activities that were performed at each stage. Although "Insights" is not a formal stage at the Design Thinking Methodology, it was included to illustrate how information and feedback are synthesized to complete the iterative cycle.

Table 1. An example of a table.

Stage	Activities / Goal	For this project
Empathize	Investigation and prior knowledge of the topic for understanding the problem scope and its context.	A search of the State of the Art was carried out to find articles, patents, and research lines that serve as background information for defining the viability of the conceptual proposal. Results of this stage are presented on section 2 of this paper.
Define	Organization of collected information while establishing coherent findings.	Information was filtered and organized based on findings. Tables and charts for comparing advantages, disadvantages, and research gaps are useful for selecting one concept to develop. Findings for this stage are presented on section 3 of this paper.
Ideate	Transformation of analyzed information into creative concepts and potential problem-solving ideas.	The analyzed information is then applied from an engineering perspective to create different concepts as potential solutions.
	Selection of one concept for design development.	By selecting one concept, the development begins. The conceptual design is proposed, specifically focusing on the high-level electrical design concept as functionality is fundamental for the technology implementation. Results are presented on section 4 of this paper.
Prototype	Development of high-level system diagrams to guide solution implementation.	The conceptual design enables the scenario to be modeled and evaluated. In this paper, the circuit proposal and components considered are presented in section 5.
Test	Justification of ideas through structured argumentation and testing results.	Based on theory and experimentation, results are presented for the conceptual proposal. These results are presented in section 6.
Insights	Evaluation of the process, outcomes reflection, improvements identification and iteration learnings.	As this is an iterative method, feedback and experimentation is used for further prototyping and proposal refinement.

5. Conceptual proposal

The high-level proposal is presented in this section as it was chosen as the selected concept for further development. This proposal includes two sections: The first one regarding the bacteria elements, which is mentioned in this section

as the "micro-system". The second section including the electrical system including the microcontroller and the sensors.

In environments and scenarios with limited accessibility, such as sewage pipes or the depths of mines, a pre-prepared micro-system can be employed. This micro-system contains *Geobacter Sulfurreducens* (GS) along with its necessary nutrients (acetates generated from another bacteria, e.g. *Acetobacterium woody*) and optimal conditions (both bacteria are anaerobic, then they will need an oxygen free container, with neutral pH and 30-35°C temperature [11]) to ensure multiple life cycles, facilitating straightforward reproduction and development processes. The GS bacteria can live in symbiosis [12], ensuring the *Acetobacterium woody* receives the appropriate substrates to sustain its metabolic function and support acetate generation; these substrates can be inorganic gases (H2 and CO2) or simple organic components to be fermented (e.g., fructose). Additionally, the microsystem incorporates a conductive medium and durable electrodes (made of carbon fiber, graphite [13] or graphene), which collectively extend the lifespan of the microgenerator and favor biofilm formation. This setup is connected to the electrical system, integrated by one or various low-energy-consumption sensors, equipped with energy dissipators to prevent damage from unexpected surges of energy.

Monitoring gases, temperature, and humidity within sewer pipelines and mining environments is crucial in ensuring safety and system reliability. These confined spaces can harbor toxic or explosive gases such as methane and hydrogen sulfide [14]; this makes early detection essential to prevent accidents and protect human lives. In mining, workers often operate in deep, enclosed, and poorly ventilated areas, and real-time monitoring is especially vital to avoid exposure to hazardous conditions. Remote sensing technologies offer a safer and continuous control alternative to manual inspections by enabling data collection at short intervals, instant alerts, and reduced risk for personnel. Beyond improving occupational safety, this approach supports predictive maintenance strategies and operational cost savings, representing an innovative, sustainable solution for modern infrastructure and industrial management.

Once the gadget is installed, it is intended to be useful for several months (considering that the bacteria can take the nutrients from the soil, sediments, and gases, or with continuous organic substrates supply), by enabling a functional microsystem in which the bacterial life cycle itself ensures continuous population regeneration. This eliminates the need to continuously supply power to geolocation devices and sensors measuring gas, pressure, light, and humidity, depending on the specific application.

6. Mechanical and electrical considerations

Although the mechanical system design is planned as future work, several considerations regarding the interaction between bacteria and the micro-system can be examined in the conceptual proposal: Maintaining separation of *Geobacter Sulfurreducens* from the micro-system is essential to prevent premature sensor activation. Therefore, a capsule containing the bacteria and its release mechanism represents a key component of the conceptual exploration. This system would require a dissolution solution with agents that break down the capsule wall, while the capsule itself must be constructed from materials that the bacteria cannot metabolize.

Additionally, preventing contamination by unwanted microorganisms within the micro-system is equally critical and should be addressed in subsequent work by specifying the material container with the appropriate sealants and internal linings suitable for the applicable conditions and effective isolation of the micro-system, as the GS bacteria needs to be in its functional, active state for long-term operation.

During operation of the electrochemical process, thin-gauge electrodes are employed to collect the electrical output, as minimizing resistance and energy loss is essential given the low current prior to powering electronic devices.

In terms of electrical considerations, Serment experiments with GS bacteria [2] reported voltage measurements consistent with those of Oh [15]: yielding approximate values of 330 [mV] and 324 [mV]. These values were rounded to V=0.3 [V] for use in the conceptual proposal, serving as the reference point for the voltage that could be obtained from the GS electrochemical process.

6.2 Electrical components

The high level diagram of the electrical connections is proposed next:

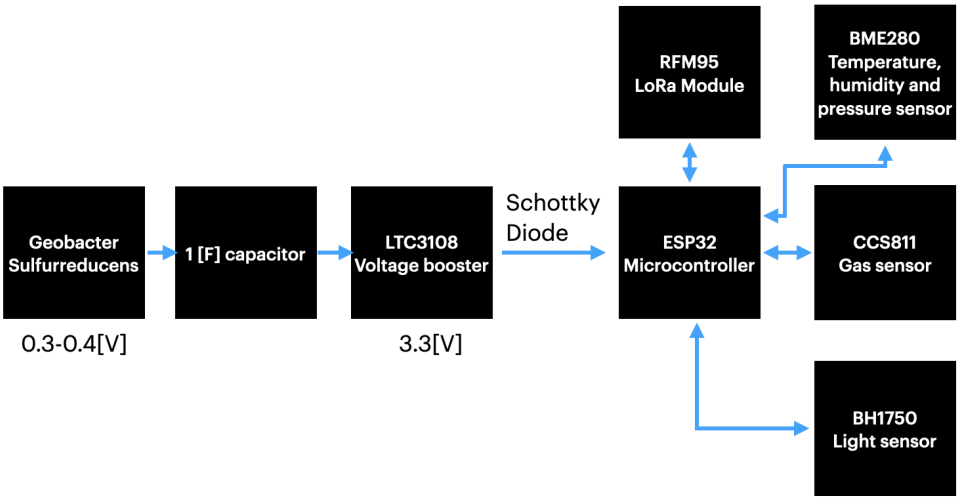


Fig. 1. High level diagram of the electrical connections.

The considered devices are the following:

1. 1 [F] capacitor for storing charge. As a low input voltage is received from bacteria, a large capacitor is connected in parallel for gradually accumulating energy over time, increasing the boost converter to draw short bursts of higher power when needed. Moreover, the input voltage may experience fluctuations due to bacteria activity or environmental conditions. The capacitor acts as a voltage stabilizer.
2. LTC3108 Boost Converter for elevating the voltage from 0.3 - 0.4 V to 3.3 V. For startup, the 1 [F] capacitor provides the threshold needed for the device to begin its operation. This boost converter needs an inductor, e.g. Coilcraft (LPR6235 series).
3. BAT54 Schottky diode for protecting the connection. To safeguard the microcontroller, the diode is place at the output of the booster to block reverse current.
4. ESP32 Microcontroller in sleep mode configuration as it consumes as little as 0.15 mA [16].
5. RFM95 LoRa (Long Range) module enables low-power, long-range wireless communication for IoT applications in remote environments. This module is used for sending data acquired through the sensors.
6. BME280 module (Temperature, humidity and pressure) with a voltage range operation from 1.7 to 3.6 [V] [17]
7. CCS811 gas sensor with a voltage operation between 1.8 and 3.3 [V] [18]
8. BH1750 light sensor with a voltage range operation between 2.4 and 3.6 [V] [19]

Current and voltage operation ranges per component are presented in table 2, based on each datasheet and the operation mode, the current consumption was registered.

Table 2. Current and voltage operation per device

Component	Current [mA]	Operational Voltage [V]
Schottky Diode (BAT54)	0.001	3.3
ESP32	0.15 (deep sleep mode)	3.3
LoRa Module (RFM95)	12.1 (Receiver mode)	3.3
BME280 Sensor	0.0036	3.3
CCS811 Gas Sensor	0.7 (average over a pulse cycle)	3.3
BH1750 Light Sensor	0.19	3.3

This article aims to explore the use of the bacteria in real-world scenarios, where environmental conditions cannot be fully controlled. As a result, various external factors may act as variables. Further work aims to ensure that these variables do not compromise the functionality or performance of the energy generator.

Boosting voltage from 0.3 to 3.3 V (approximately an 11-fold increase) is crucial to supply adequate power for the microcontroller, sensors and the LoRa communication module. To optimize energy efficiency, it is essential to operate these components in cycles, minimizing continuous current drain. In addition to managing communication, the microcontroller is responsible for activating the sensors only at a predefined time intervals. This operation reduces unnecessary power consumption, ensuring the system remains functional even under limited energy availability.

As shown on table 2, components can operate at low current levels. However, further analysis is required to determine whether the input current to the booster converter and its efficiency are sufficient to power the entire electrical system. Future iterations should address an initial sensor configuration for proper calibration of the acquired data, since environmental factors such as temperature, humidity, and local pressure can significantly affect measurement accuracy.

Functional prototypes and experimental tests will be necessary to better evaluate the proposed electrical performance. Additionally, the mechanical design and material selection of the model must consider the electrical requirements and measurement constraints of the devices. Therefore, subsequent iterations should also focus on modeling and testing the enclosure, optimizing component distribution within the device and material selection for the case system.

Given the nature of the scenarios where this proposal is intended to be implemented, redundancy could be a critical design consideration to ensure continuous operation and reliable data acquisition, even in the event of individual sensor or component failure. For example, in mining applications, where workers safety is paramount, redundancy can provide an additional layer protection by minimizing the risk of data loss or incorrect measurements that could compromise operational decisions.

7. Conclusions

This work presents a conceptual proposal for using *Geobacter sulfurreducens* (GS) as the power source for a low-consumption circuit for monitoring several variables. This work still requires validation and testing to determine its practical feasibility. It marks the initial stage on an exploratory study in which a system is proposed for powering low-consumption data acquisition components using accessible materials and technologies. The design prioritizes simplicity and availability of the parts to ensure ease of implementation. The next phase involves building and testing the system to assess its viability and to identify suitable application areas through experimental validation. The conceptual design is grounded in existing literature that includes experimentally supported technology. In the context of Industry 4.0 and its application in remote challenging scenarios, this project offers an alternative approach for environmental monitoring. The proposed system is designed to have a low environmental impact, affordable

operational costs, supporting data-driven decision making. The proposal includes a voltage booster capable of powering an ESP32 microcontroller, a LoRa module for wireless communication and three sensors: a BME280 for measuring temperature, humidity and pressure; a CCS811 for detecting air quality and gas concentrations; and a BH1750 for ambient light measurements.

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