Powering a Microprocessor by Photosynthesis

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Abstract

Sustainable, affordable and decentralised sources of electrical energy are required to power the network of electronic devices known as the Internet of Things. Power consumption for a single Internet of Things device is modest, ranging from μW to mW, but the number of Internet of Things devices has already reached many billions and is expected to grow to one trillion by 2035, requiring a vast number of portable energy sources (*e.g.*, a battery or an energy harvester). Batteries rely largely on expensive and unsustainable materials (*e.g.*, rare earth elements) and their charge eventually runs out. Existing energy harvesters (*e.g.*, solar, temperature, vibration) are longer lasting but may have adverse effects on the environment (*e.g.*, hazardous materials are used in the production of photovoltaics).

Here, we describe a bio-photovoltaic energy harvester system using photosynthetic microorganisms on an aluminium anode that can power an Arm Cortex M0+, a microprocessor widely used in Internet of Things applications. The proposed energy harvester has operated the Arm Cortex M0+ for over six months in a domestic environment under natural light. It is comparable in size to an AA battery, and is built using common, durable, inexpensive and largely recyclable materials.

Introduction

The Internet of Things (IoT) comprises a vast network of small computational devices deployed in domestic, commercial, industrial and natural environments, connected to a myriad of "things" for sensing and transmitting their status, responding and communicating accordingly. This network has revolutionised many aspects of the modern world and will transform information exchange in smart homes, cities, factories, farms and natural environments[1-3]. The IoT is growing rapidly. With several billion IoT devices already in existence[4], it is expected to reach one trillion by 2035[5]. Many IoT devices consume power in the range of µW to mW, and are frequently powered by a battery. However, powering one trillion IoT devices by lithium-ion batteries, would require 109,000 tonnes of lithium, three times more than the world's annual production in 2017[6], and not sustainable. Other battery types would also require major use of natural resources, or routine recharging and eventual replacement with inevitable negative environmental impact[7,8]. Consequently, energy harvesting - rather than energy storage - is desirable for powering IoT devices[9]. The ideal energy harvesting system must deliver sufficient power for continuous sensing[10], and should be built using inexpensive and common materials, avoiding toxic components.

To date, examples of energy harvesting systems for IoT devices include photovoltaics (PV)[11], microbial fuel cells (MFC)[12], and other micro-scale energy harvesting materials[13]. PV are arguably the most studied, developed and perhaps most immediately practicable[14]. However, they do not provide power during dark periods. Microbial fuel cells (MFCs) use bacteria to oxidize a chemical fuel and generate electrical energy[15]. Although they can operate in the dark, MFCs depend on the metabolism of heterotrophic bacteria and require a supply of organic matter[16]. Photosynthetic microorganisms can be used instead of heterotrophic bacteria in the anodic chamber of these biological fuel cells. Such devices are often referred to as biophotovoltaics (BPV) as the electric current is ultimately based on electrons liberated from water through photosynthetic photolysis of water[17-19]. This removes the need to supply the device with organic matter as chemical fuel, and uses solar energy to drive it. One of the key components in BPV devices is the anode, which channels the current generated by the microorganisms into an external circuit. The ideal anode must be biocompatible, with adequate electric conductivity and optical properties to permit current flow and light diffusion. For BPV devices to be implemented at large scale, the anode should be durable and use abundant and low-cost materials[20-21].

Here, we report the development of a novel aluminium-anode bio-photo-voltaic system (Al-BPV) with as photo-active component the commonly used model photosynthetic bacterium *Synechocystis sp.* PCC6803 (hereafter referred to as Synechocystis). The system was built in a small form factor (*i.e.*, small size) using common, durable, and recyclable materials. The system successfully and continuously powered for over six months a microprocessor based on an Arm Cortex M0+ central processing unit (CPU), one of the most commonly used CPUs found already in many commercial IoT applications. The test was conducted in a domestic environment without any dedicated artificial lighting system, additional battery or organic fuel supplement. The mechanism of operation of the Al-BPV system was studied using electrochemistry (cyclic voltammetry, potentiodynamic sweep and electrochemical impedance spectroscopy), microscopy, and microbiological characterisation.

This study demonstrates the robustness and practicability of an Al-BPV as a durable and reliable source of renewable power for untethered applications, paving the way for the large-scale implementation of photosynthetically powered micro-electronics.

Results and Discussion

Rationale for using aluminium as anode

To select an optimal anodic material to be used in photosynthetically driven electrochemical systems, aluminium was considered because it is one of the most abundant metals in the Earth's crust, available in large quantity as waste in the environment, and classified as not toxic[22]. The use of an aluminium anode in electrical energy generation systems has been described before, in aluminium-air batteries (AAB)[23]. In these, electrochemical aluminium oxidation in an alkaline medium is combined with oxygen reduction at the cathode. To our knowledge, the effect of introducing biological components into AAB has not been studied. Several studies have examined the physiological effects of aluminium on plants, cyanobacteria and microalgae, with results depending on the organism considered[24-25]. We tested growth of Synechocystis cultures in the presence of metallic aluminium, and found that they reached a cell density similar to control samples without aluminium (**Fig.S1**), suggesting that aluminium is biocompatible with Synechocystis.

Light-dependent power production from a prototype Al-BPV

We built a prototype BPV system (Al-BPV) using aluminium wool as anode (**Fig.S2**), with a commercial open-air cathode, stainless steel electric connectors and plastic vessels (**Fig.S3**). The prototype Al-BPV system was inoculated with Synechocystis (**Fig.S4A**), and first tested in a laboratory-controlled environment. The system gave peak power density of 0.2 $\mu W\ cm^{-2}$ and 0.37 $\mu W\ cm^{-2}$ under dark and light conditions respectively, indicating a photoactive component to power production. These figures were significantly greater than those observed in an abiotic negative control (**Fig.S4B**). The effect of illumination on the electrical output observed here in the prototype Al-BPV system is not seen in AABs, which are not photo-active when illuminated with visible light[26], although in AABs a modest increase in the power output in response to light might be observed because of the thermal effect of illumination[27]. Thus, the presence of a much bigger photo-effect in the presence of Synechocystis compared to the abiotic control (**Fig.S4B**), and the large increase in amplitude in response to increased light intensity (**Fig.1A**) indicate that current production depends on the photo-active component of the system, (*i.e.*, the photosynthetic microorganisms). The effect of adding the photosynthesis inhibitor 3-(3,4-dichlorophenyl)-1,1-dimethylurea (DCMU)[28] to the anodic chamber was tested. DCMU addition had an immediate effect on photo-current (**Fig.1B**), which stopped increasing and then decreased. The effect of inactivating the photosynthetic microorganisms was tested by autoclaving the inoculated anode. This abolished autofluorescence, indicating loss of photosynthetic activity, and resulted in almost complete loss of light-dependent current (**Fig. S5**). These observations indicate that current production from the Al-BPV depends on the biological activity of the microorganisms.

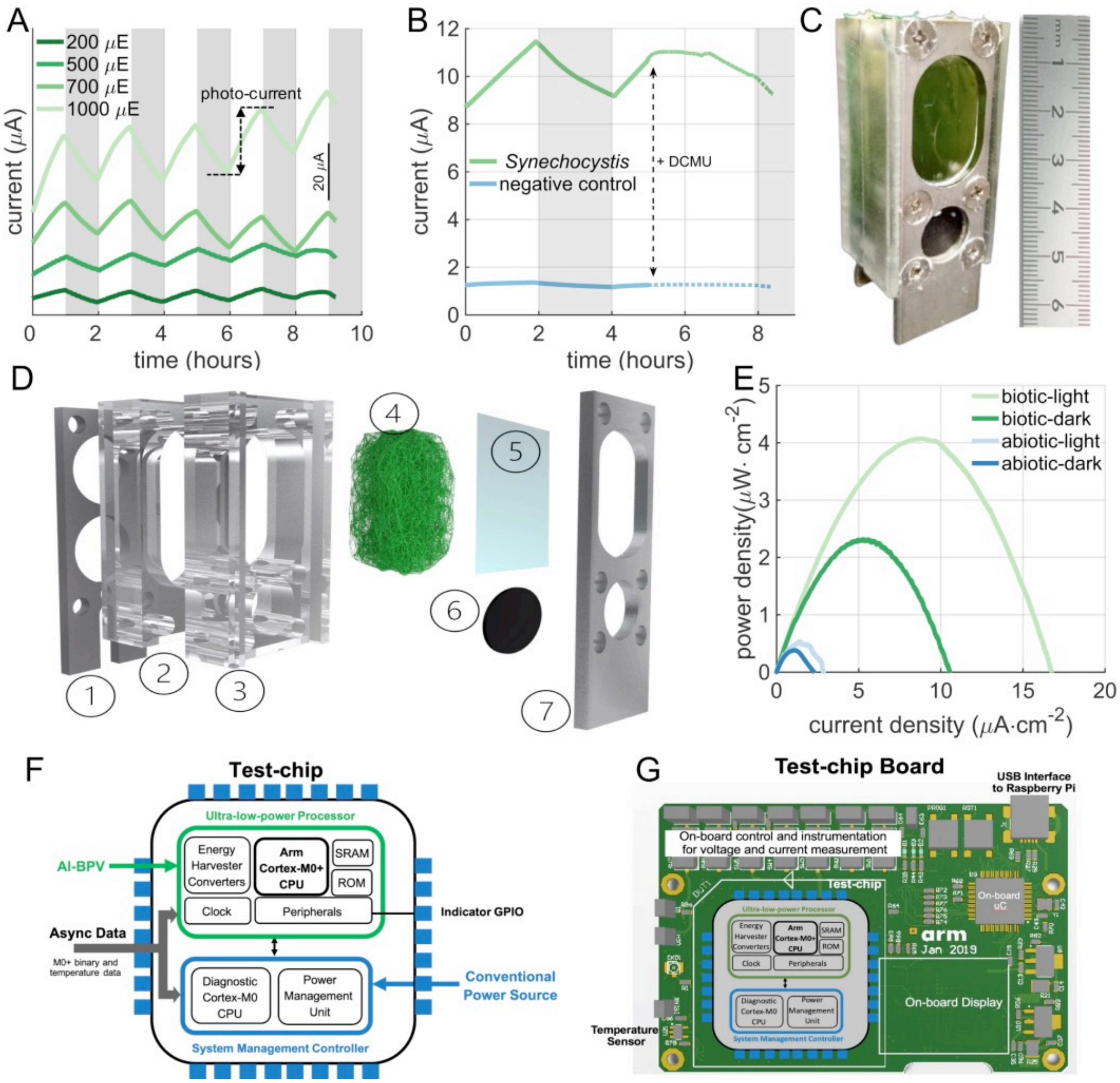

Fig. 1. Development and characterisation of the prototype and compact Al-BPV systems, and diagrams of the Arm Cortex-M0+ processor in a test-chip and board. **A**) Chronoamperometry for the prototype Al-BPV system under 2 hours dark/light cycles. Effect of increasing light intensities on the photo-current. **B**) Effect on photocurrent for the prototype Al-BPV system of addition of the photosynthetic inhibitor DCMU (35 μM), including for the abiotic negative control with BG11 medium only (blue). **C**) Photograph of the compact Al-BPV system. D) 3D exploded diagram of the compact Al-BPV system. The diagram shows two stainless steel metal plates (1 and 7), an acrylic compartment made of two parts (2,3), an aluminium anode colonised with photosynthetic microorganisms (4), a Teflon gas-permeable membrane (5) and an open air cathode (6). Stainless-steel screws are not shown in this diagram. **E**) Power curve for the compact Al-BPV system and abiotic negative control (BG11 only) (scans at rate of 0.1 mV s^{-1}). **F,G**) Schematic diagrams of the test-chip and its board. The test-chip includes two blocks: an ultra-low-power processor consisting of an Arm Cortex-M0+ CPU, SRAM, ROM, clock, peripherals, and energy harvesting converters, and a system management controller consisting of a diagnostic Arm Cortex-

M0 CPU and a power management unit. The Al-BPV powers the ultra-low-power processor whilst the system management controller is powered by a USB power source. The test-chip board contains the test-chip, a temperature sensor, voltage and current measurement circuitry, a microcontroller taking the voltage, current and temperature measurements, a display and a USB interface to an external Raspberry Pi. The Arm Cortex-M0+ requires a minimum of 0.3 μW (at 0.3V) to run its computational work at a frequency of 10 kHz. The minimum power consumption drops to 0.24 μW during the standby mode when computations are not running. The system management controller in the test-chip was powered by a conventional USB power source.

Developing a compact Al-BPV for powering the Arm Cortex-M0+ in a domestic environment

Having demonstrated the possibility of power generation in an Al-BPV system, we constructed a compact version with a small form factor, similar in size to an AA battery, referred to as the compact Al-BPV (**Fig.1C-E** and **Fig.S6,7**). Characterisation in a controlled laboratory environment (**Fig.S8**) showed a peak power density of 4.2 μW cm^{-2} and an output maintained for over 20 days. This should be sufficient to power a real-world device, such as the Arm Cortex-M0+ CPU[29]. This is a programmable 32-bit RISC microprocessor, highly energy- and area-efficient, supporting the ARMv6-M Thumb instruction set (**Fig.1F**). The Arm Cortex-M0+ is used in many microcontrollers and embedded applications that can run programs written in high-level programming languages. In the experiments, we used a test-chip designed and implemented by Arm[30-31] comprising the Arm Cortex-M0+ and a system management controller (**Fig.1G**).

We programmed the Cortex-M0+ CPU to calculate a sum of consecutive integers (S_n) as an example compute workload, and assess the correctness of the computation by verifying the sum against a precomputed value ($S_n = \frac{n(a_1+a_n)}{2}$). We programmed the CPU to perform 45 minutes of computation work followed by 15 minutes of standby (**Fig.S9**).

The test was conducted over half a year in a domestic setting in Cambridge (UK), with ambient light as the energy input (**Fig.S10**). The anode-to-cathode voltage, current, ambient temperature and light were measured by the electronics built in the test-chip board and then recorded and visualised on the cloud-based platform ThingSpeak™ via a Raspberry-pi/router (**Figures 2 and S11)**. During the test, the Arm Cortex-M0+ processor performed a total of 1.23E+11 cycles, resulting in a linear and continuous increase in the number of calculations performed over time (**Fig.2A-C**). Throughout the test, the Arm Cortex-M0+ processor drew an average current from the compact Al-BPV of 1.4±0.4 μA with a voltage of 0.72±0.14 V (**Fig.2D-I**). The light profile displayed the expected diurnal cycle (**Fig. 2J-L**) with ambient temperature ranging from a minimum of 13.8 °C to a max of 30.7 °C (**Fig. 2M-O**). As the average power drawn from the compact Al-BPV during the 27 weeks of experimental run (1.05 μW) was larger than the minimum power required to run the CPU (i.e., 0.3 μW), it is likely that a smaller power-generating system could be used, or that more computationally intensive algorithms could be performed.

The system was set up so that if the CPU failed, e.g., the compact Al-BPV cannot supply minimum operating power, the processor would automatically be switched to the mains electricity (USB powered). This would be displayed by recording a voltage >5V, and the system would need to be reset. To test this, we deliberately induced failure (for about 90 minutes at the end of the third week) by positioning an ice-pack near the temperature probe mounted on the test-chip which caused a localised lowering of the ambient temperature below 5 °C (**Fig.2M** red background), which is much below the minimum operating temperature 13.8 °C, without varying the temperature experienced by the compact Al-BPV. In this instance, the software controlling the operation of the CPU triggered to switch the power of the CPU from the Al-BPV to the USB power supply. Apart from this instance, switching to >5V was not observed at any other time during the experiment shown in **Figure 2**, indicating that the CPU was powered successfully throughout by the Al-BPV. The system also incorporated an LED that flashed when the CPU was powered by the Al-BPV. Failure of the Al-BPV to power the CPU would cause the LED to stop flashing until the system was reset. Failure was not seen at any time during the experimental run except when deliberately induced.

The current and voltage profile recorded during the six months of testing (**Fig.2D-G**) did not show consistent decline by the end of the test, and the system was still running on the date of submission of this manuscript (2022/01/19 - see Channel 1033008 (https://thingspeak.com/channels/1033008) of the ThingSpeak™ platform (**Fig.S11**)). The durability of the compact Al-BPV system was also demonstrated in a parallel experimental test run for more than four months (**Fig.S12**). This test was stopped for analysis of the anode and anodic microbiome (see below). A larger prototype has remained functional for over two years (**Fig.S13**)**.** To our knowledge, this study is the first to report continuous powering of a microprocessor using a bio-electrochemical system driven by photosynthetic microorganisms with ambient light as the sole energy input, without the need for any additional battery, or organic fuel and outside of laboratory-controlled conditions.

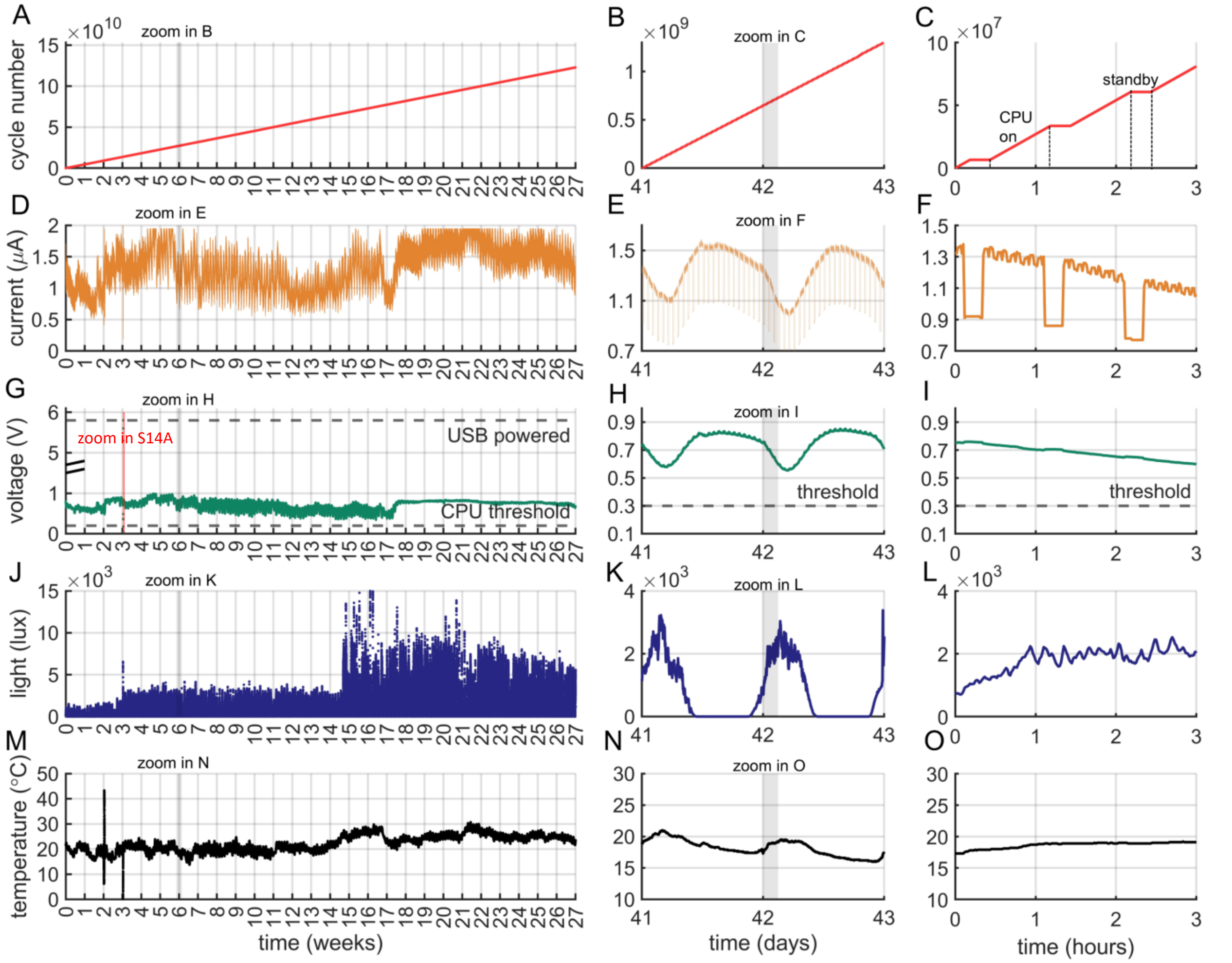

Fig. 2. Powering the Arm Cortex-M0+ processor by the compact Al-BPV system in a domestic environment (from 2021/02/20 to 2021/08/02)**.** The CPU alternated in cycles of 45 minutes of computing mode and 15 minutes of standby. The data presented in the left column (**A**,**D**,**G**,**J** and **M**) show the entire experimental run. Central columns (**B**,**E**,**H**,**K** and **N**) illustrate insets of two days of recording taken from an arbitrary point (depicted by the gray-shaded regions) of the left column. The data presented in the right column (**C**,**F**,**I**,**L** and **O**) show three hours of recording taken from an arbitrary point (depicted by the grey-shaded regions) of the central column. **A-C**) Cumulative number of cycles of the sum of consecutive integers computed by the CPU. **D-F**) Electrical current generated by the BPV device. **G-I**) Absolute potential difference between the anode and cathode of the BPV device. The dotted line indicates the threshold of electric potential below which the processor cannot be powered. **J-L**) Ambient light measured by a light sensor placed in proximity to the Al-BPV system. **M-O**) Environmental temperature measured by a temperature sensor integrated into the test-chip board. The red-shaded regions depicted in panels **G** and **M** indicate a phase during which the Al-BPV failed to power the CPU induced by deliberately lowering the ambient temperature below 5 C°, as zoomed in **Fig.S14**).

Working hypothesis for the mechanism of operation of the Al-BPV system

There are two possible modes of operation for the Al-BPV, which we refer to for simplicity as 'electrochemical' and 'bio-electrochemical' modes. Although both rely on the photosynthetic activity of the microorganisms in the anodic chamber, in the electrochemical mode, the photosynthetic microorganisms do not directly generate current responsible for the electrical output. Instead, they provide a favourable environment for aluminium oxidation, *e.g.,* through local alkalinization, and electrical output stems from current derived from electrochemical aluminium oxidation. In this electrochemical mode the Al-BPV system works as a photosynthetic microbially assisted aluminium air battery (**Fig.3A**). By contrast, in the bio-electrochemical mode, the photosynthetic microorganisms themselves generate the electrons constituting the electrical output of the Al-BPV system. Electron transfer would presumably occur via the outer bacterial membranes through the extracellular matrix to the aluminium, perhaps involving secreted electron shuttles[32] (**Fig.3B**). It is possible that both modes coexist and the predominant mode changes over time.

A number of analyses were carried out to assess the importance of the two modes. Optical microscopy and scanning electronic microscopy (SEM) of filaments of aluminium taken from a device that had operated for four months showed a dense layer of material had built up on the anode, possibly including oxidation products and biofilm components (**Fig.3C-F, S15**). This layer, accumulated over time, would be expected to limit further aluminium oxidation. We also carried out cyclic voltammetry (CV) analysis on aluminium hydroxide and extracellular matrix scraped from the anode of a mature Al-BPV system. CVs showed oxidation and reduction peaks indicating the presence of one or more redox active species (**Fig.3G**), which could most readily be explained if they were generated by microorganisms at the anode. Electrochemical impedance spectroscopy (EIS) measurements showed that the Rp of a bare Al anode was approximately two-fold greater than that of the anode taken from an Al-BPV system four months old (**Fig.3H**). However, a potentiodynamic sweep (PDS) curve (**Fig.3I**) of new aluminium filaments without biofilms submerged in BG11 medium showed only a weak increase of current with potential in the anodic branch (the region with potential increasing from ca. -0.3 V), thus excluding pitting (i.e., fast dissolution of aluminium). The PDS curve of the colonised aluminium (**Fig. 3I**) also did not show a strong current increase in the anodic branch. From these measurements, there is no indication that anodic polarisation would lead to fast corrosion of the aluminium surface in new or colonised filaments, consistent with the fact that although microbially influenced corrosion is known to affect iron, it is much less common on aluminium[33]. Although bacteria are known to affect aluminium alloys in chloride-rich environments (*i.e.,* seawater)[34,35], the mineral medium used in our study had a low chloride concentration (~0.5 mM), making microbial corrosion less likely.

In summary, the amount of material deposited on the anode increased with time, and the polarization resistance decreased with time. The PDS data indicate that fast corrosion of the aluminium was not occurring. The decrease of the polarisation resistance may indicate modification of the aluminium oxide layer by the microorganisms, facilitating electron transfer through the usually insulating oxide. The persistent current output and photo-response seen in Al-BPV systems several months old even when the anode was covered with passivating components suggest the bio-electrochemical mode makes an important contribution to electrical output with mature systems. A mixed, dynamic scenario, with a change in the relative importance of the two modes could explain the variation of current output observed during the long-term operation of the Al-BPV (*e.g.*, **Fig2.D,G** and **Fig.S12D,G**). The electrical connection of the microorganisms to the electrode would presumably depend on factors such as their adhesion, the build-up of material on the electrode, and the production of redox mediators by the microorganisms. These properties would affect the performance of the device as an energy harvester. For future applications, microorganisms could be selected to optimize the relevant properties.

We also sequenced prokaryotic ribosomal RNA genes from DNA extracted from cells in a compact-Al-BPV system that had initially been inoculated with cells of the cyanobacterium *Synechocystis*, but then operated for several months in a non-sterile domestic environment. Evidence was found for a complex biome containing a wide range of microorganisms, including representatives of *Halomonas* and *Pseudomonas* (**Fig.3J**), genera which include electroactive bacteria[36-37]. These microbes might provide redox active electron shuttles (which many electroactive bacteria are known to do[38]), and/or oxidise organic metabolites received from the photoautotrophs, transferring electrons to the anode (**Fig.S16**). Having a consortium of microorganisms in the anode compartment, with photoautotrophs and heterotrophs sharing different functions, may offer enhanced stability and less susceptibility to contamination[39-40]. The change in current output seen over time in long-running experiments (e.g., **Fig.2D**) might reflect a change in microbial composition.

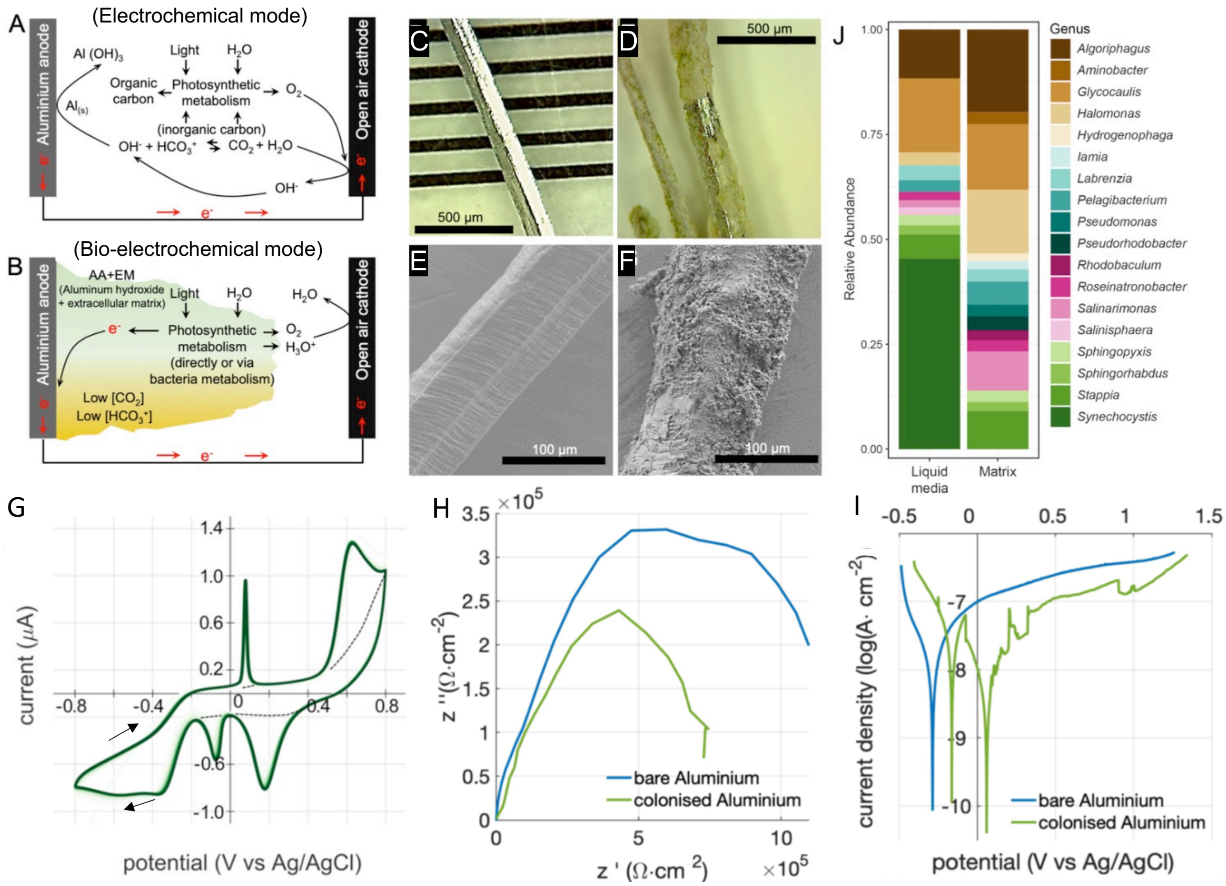

Fig. 3. **Proposed mechanisms of operation of Al-BPV system**. **A**) Diagram illustrating the processes during the proposed electrochemical operational mode. **B**) Diagram illustrating the processes during the proposed bio-electrochemical operational mode. **C,D**) Optical microscopy of new (**C**) and colonised aluminium anodes (**D**). **E,F**) Electron microscopy of new (**E**) and colonised aluminium anodes (**F**).**G**) Cyclic voltammetry performed on a sample of aluminium hydroxide and extracellular components scraped from an aluminium anode taken from an Al-BPV system several months old (21 scans at rate of 10 mV s^{-1}, Screen-Printed Gold Electrode C223BT. **H**) Electrochemical impedance spectroscopy on a bare aluminium anode in BG11 growth medium without microbes (blue trace) and a colonised aluminium anode (green trace). The diameter of the semi-circle in the plot corresponds approximately to the polarization resistance Rp. **I**) Potentiodynamic sweep on bare aluminium anode submerged in BG11 growth medium without microbes (blue trace) and colonised aluminium anode (green trace). **J**) Identification by ribosomal RNA sequencing of the prokaryotic microbiome found in the liquid phase and matrix (aluminium hydroxide and extracellular components). Sample was taken from an Al-BPV system after four months of operation in a domestic environment.

Conclusion

We have developed a novel aluminium-anode biophotovoltaic system (Al-BPV) based on widespread non-toxic photosynthetic microorganisms (*Synechocystis*) built using common, durable, inexpensive and largely recyclable materials (**Fig.1C-D, S2, S6-S7**).

The compact Al-BPV is comparable in size to an AA battery, and it is capable of powering the Arm Cortex M0+ processor (**Fig.1F,G** and **Fig.S11**) for more than six months in a domestic environment without any subsidiary energy storage device, artificial lighting or organic feeding (**Fig.2**).

We propose the Al-BPV system as a practical alternative to PVs and MFCs for powering small electronic devices for numerous domestic, industrial and agricultural applications, and potentially in remote locations. Our system has a unique place in the landscape of this technology (**Fig.S17, Table S1**) and paves the way for the development and implementation of a vast number of photosynthetically-powered IoT devices.

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Competing interests

CJH and PB hold Patent GB2466415 - Hydrogen and electrical current production from photosynthetically driven semibiological devices.

Data and materials availability

The data that support the plots within this paper and other findings of this study are available at: https://doi.org/10.17863/CAM.74822

Supplementary Materials:

Figs. S1 to S17

Tables S1

Materials and Methods