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Scale-up of sediment microbial fuel cells

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HIGHLIGHTS

- SMFCs can be scaled up electronically.
- Scaled-up SMFCs produced higher power than parallel connected SMFCs.
- Scaled-up SMFCs with a PMS generated higher power.
- Microbial communities do not play a role in scale up.

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ABSTRACT

Sediment microbial fuel cells (SMFCs) are used as renewable power sources to operate remote sensors. However, increasing the electrode surface area results in decreased power density, which demonstrates that SMFCs do not scale up with size. As an alternative to the physical scale-up of SMFCs, we proposed that it is possible to scale up power by using smaller-sized individually operated SMFCs connected to a power management system that electrically isolates the anodes and cathodes. To demonstrate our electronic scale-up approach, we operated one 0.36-m^2 SMFC (called a single-equivalent SMFC) and four independent SMFCs of 0.09 m^2 each (called scaled-up SMFCs) and managed the power using an innovative custom-developed power management system. We found that the single-equivalent SMFC and the scaled-up SMFCs produced similar power for the first 155 days. However, in the long term (>155 days) our scaled-up SMFCs generated significantly more power than the single-equivalent SMFC (2.33 mW vs. 0.64 mW). Microbial community analysis of the single-equivalent SMFC and the scaled-up SMFCs showed very similar results, demonstrating that the difference in operation mode had no significant effect on the microbial community. When we compared scaled-up SMFCs with parallel SMFCs, we found that the scaled-up SMFCs generated more power. Our novel approach demonstrates that SMFCs can be scaled up electronically.

1. Introduction

Remote sensors have been used to monitor the environment continuously [1]. However, the long-term use of remote sensors is generally limited by the finite charge stored in deployed power sources. Traditionally, the primary power source used has been disposable batteries. When batteries are used, the cost of replacing them becomes problematic; in many cases, operating the remote sensors for an extended period of time is not logistically feasible or sustainable. In addition, the toxicity of certain types of batteries makes their use less acceptable when their environmental impact is considered. Therefore, alternative renewable remote power sources are required to replace batteries. These alternative power sources should produce power from renewable sources where the sensors are deployed. In addition, they should not require maintenance. A promising alternative renewable, low-maintenance remote power source is the sediment microbial fuel cell (SMFC), which is a subgroup of the well-known microbial fuel cells (MFCs).

Recently, we showed that MFCs, including SMFCs, cannot be scaled up to give higher power densities for a specific configuration [2,3]. Surprisingly, it is still commonly believed that the scale-up of low power generating MFCs will not be a problem. Ref. [4] claimed that 100 W m^{-3} would be easily reached [4]. Similarly, Ref. [5] in their review claimed that scale-up could be accomplished by stacking MFCs [5]. Interestingly, Ref. [6] used small, 30-mL, MFCs to

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show that scaling up could generate an estimated 4.3 W m^{-2} [6]. We should note that these are power density estimates and there is currently no MFC which produces even 1 W, let alone 4.3 W, in any configuration. Although it has been claimed that MFCs can produce power densities up to several W m^{-2} or W m^{-3}, to the best of our knowledge there is currently no MFC which can produce Watt-level power unless that power is harvested and used intermittently. For example, using a custom power management system developed by our research group, we demonstrated the intermittent powering of a 2.5-W remote sensor [7]. The sensor was operated intermittently because the MFC produced on average 3.4 mW of continuous power. It was only possible to generate the Watt-level power needed to operate this system by storing the energy in a capacitor and then using it intermittently. Without strategic use of the power produced by MFCs, any reported power density values of several W m^{-2} or W m^{-3} are misleading and cannot be related to powering Watt-level devices. All the values from the literature show the researchers' expectations to be wrong: simply, there is no 1-m^2 SMFC or MFC producing the expected Watt-level power. One way to bypass the low power generation of MFCs is to use power management systems (PMS) [7–10]. However, SMFCs or MFCs will be more useful if we can develop a scalable technology that enables continuous, Watt-level power generation. This technology should stall or eliminate the dramatic drop in current density observed when the surface area of the limiting electrode increases [2,3]. This new scalable technology could allow us to power remote sensors needing higher power for continuous operation over a long period of time.

It was initially expected that the amount of power generated by SMFCs would be a linear function of their size [11]; thus, when the surface area of the limiting electrode increased, the power was expected to increase proportionally. A necessary condition for this assertion to be true for SMFCs is that the power density not depend on the surface area of the current-limiting electrode. However, in one of our previous works and elsewhere in the literature, it has been shown that the power density decreases with increased electrode surface area [12,13]. In practical terms, this means that to double the power, we would need to increase the surface area almost 100-fold [13]. Deploying such large electrodes can be problematic: it would be very challenging to bury a 100-m^2 electrode in sediment in a remote environmentally sensitive location. In order to generate high power practically, multiple electrodes with smaller, or deployable, sizes should be utilized. When multiple electrode systems are deployed, the SMFCs cannot be operated in series because all the electrodes are ionically connected in the same solution [3,7,9,10,14]. Parallel operation is equivalent to making the electrode surface area larger. Therefore, we did not explore series operation and focused on parallel and independent operation of SMFCs in this research.

Our research group developed one of the first PMS for single SMFCs [9]. Many PMSs for SMFCs have since been developed [15–28]. Although the implemented systems are vastly different from each other, all of them follow a common path of harvesting energy from an SMFC in order to operate various electronic devices. For example, in our previous work described above, a combination of a charge pump and a dc–dc converter was used to boost the potential to a desired value, i.e. 3.3 V, to operate a wireless sensor [29]. As an alternative to our approach, a combination of a transformer and a dc–dc converter has been used for the same purpose [27]. Several PMSs have been demonstrated with multiple SMFCs [19,23,30–32]. However, the SMFCs were not operated independently. They were directly connected in parallel; i.e., the anodes and cathodes of different SMFCs were electrically shorted together. This is similar to the parallel operation of multiple SMFCs. These cannot be considered independently operated SMFCs. To be independent, SMFCs should be electrically isolated. After this problem was realized, subsequent studies showed improvement. The cathodes were isolated but the anodes were short-circuited [23,32]. Combined anodes served as a common ground reference for the whole system. Considering the anode limitations of SMFCs, the use of this system will be limited. Therefore, it is critical to have a PMS which can isolate both anodes and cathodes. We should note that many reported PMSs lacked one important characteristic, i.e., self-sustainability, or batteryless operation. Without a self-sustainable PMS, SMFCs cannot be used as a renewable remote power source. By designing a self-sustainable PMS that can harvest energy from multiple independently operated SMFCs (isolated anodes and cathodes), we can implement higher power for continuous remote sensor systems. Therefore, the goal of this research was to 1) develop a self-sustainable PMS system which can harvest energy from multiple SMFCs independently to scale up the power, 2) test this PMS system by operating multiple small SMFCs and one large, equivalent anode surface area SMFC, and 3) compare the power generation and microbial communities of the parallel and independent operation modes for the same anode surface area.

In this research we designed two different types of SMFCs; 1) a single (0.36-m^2) SMFC and 2) four independent SMFCs (0.09 m^2 each). This corresponds to two systems with identical anode surface areas but with one of them segmented. The single SMFC with a 0.36-m^2 area is called a single-equivalent SMFC when connected to our single-channel PMS. When the four SMFCs that are 0.09 m^2 each are electrically isolated by connecting them to our four-channel PMS, they become independently operated and are collectively referred to as scaled-up SMFCs. All SMFCs reported here were anode-limited. Therefore we only varied the anode surface area. This is also consistent with the literature showing that the anode is generally the limiting electrode for SMFCs used to power sensors [12]. Both systems were operated using a custom-developed PMS, and the performances of the scaled-up systems are compared with that of an alternative scale-up strategy (parallel connection of SMFCs). The SMFCs were operated more than a year. At the end of the experiment, we conducted microbial community analysis to determine whether any microbial community differences existed between the anodes of the single-equivalent SMFC and those of the scaled-up SMFCs.

2. Materials and methods

2.1. Sediment microbial fuel cells and their components

Fig. 1 shows a schematic diagram of the SMFCs and their components. The SMFC in Fig. 1A consists of two electrodes, an anode (1.2 m by 0.3 m by 0.006 m, for a projected surface area of 0.036 m^2) and a cathode, and a single-channel PMS. The SMFC in Fig. 1B consists of eight electrodes, four anodes (each 0.3 m by 0.3 m by 0.006 m, for a projected surface area of 0.09 m^2) and four cathodes. The PMS electrically isolates each pair of electrodes. These laboratory-scale SMFCs were deployed in 265-L plastic containers with a working volume of 240 L. The anodes and the cathodes were made of graphite felt (HP Materials Solutions, Inc., Woodland Hills, CA 91367, USA). The relative locations of the anodes and cathodes are shown in Fig. 1. The anode and the cathode were connected to the PMS using Grade 2 0.635-mm-diameter Ultra-Corrosion Resistant Titanium Wire (McMaster-Carr, Los Angeles, CA 90054) and standard copper hookup wire. Ti wires were woven into the graphite felt and secured with nylon bolts. A mechanical and solder connection to copper wire was sealed with silicone rubber to prevent water intrusion to complete the connection to the PMS. The resistance of the copper wire, Ti wire and graphite felt connections was less than 1 Ω at every point measured around each electrode.