Microbial Fuel Cells powering robots and beyond; historical perspective and future directions

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Abstract
This position paper presents part of the history of Microbial Fuel Cells development for practical applications. The paper gives examples of real-world implementation, learnings from field trials and how these have contributed to the fundamental advancement of the technology. Given the status of global affairs and the significance of energy security – in many cases, at the cost of access to resource - the paper also provides a perspective on the future of the technology and where it may offer a valuable utility.

Introduction
The greatest technological breakthroughs in history start from a simple, often serendipitous discovery, initially with no application in mind. It normally takes decades, if not centuries, of painstaking research and development, before a discovery takes some form of shape and offers utility. The Microbial fuel cell (MFC) technology is no exception; this paper offers some learnings from two decades' worth of intensive research & development, bringing light to the path towards commercialisation.

The increased rates of water usage and waste generation in anthropogenic activities, have driven scientists to search for alternative ways of valorising wastewater. One such alternative technology is bioelectrochemical systems that produce electricity from the breakdown of organic compounds. The first discovery related to MFCs dates back to the late 1700's, followed by the first scientific demonstration of an MFC bioreactor, nearly two centuries later. This then inspired generations over a whole century, now proposing hybrids of MFC-hydroponics and more recently, MFCs for local human waste treatment in long term extraterrestrial missions.

From frog legs to fuel cells

The first demonstration of electron flow in biological tissue was published in 1791 by the Italian physicist, Luigi Galvani [1]. This study, *De viribus electricitatis in motu musculari Commentarius*, summarised a decade's worth of research in electrophysiology. This work included the famous experiment of Galvani, which employed the legs of a dead frog to induce contractions from lightning. A little more than a century later, in 1910, Potter published his findings of the electrical effects involved in fermentation using *Saccharomyces cerevisiae* or *Escherichia coli [2].* Potter expressed in his study the need to understand how energy is being liberated given that microorganisms consume organic compounds as a source of energy, and this absorption must consequently lead to a 'desorption', most likely electrical. He demonstrated this using a galvanic cell with platinum electrodes. His experiment had all the attributes of a bioelectrical system, technically making this the first reported form of a Microbial Fuel Cell. In 1931, Potter's experimental setup was revived by Barnett Cohen to demonstrate the intensity and capacity of biological oxidation-reductions [3]. Multiple Potter-style fuel cells of 10 ml were connected electrically in series, generating a voltage of 35 V and 2 mA of current.

In the decades between the 1960s and 1990s MFCs started gaining significant attention from the scientific community. In 1967, a review on fuel cells from NASA dedicated a whole chapter to what the scientific community then coined as *biochemical fuel cells*[4]. In this work, Austin suggested three potential uses for biochemical fuel cells: (i) electricity generation in underdeveloped countries from vegetables and animal matter, (ii) the use of these cells as lightweight batteries for military purposes and (iii) their use in space travel as part of a closed loop system where human food and waste are re-used. He recognised that the low power production remained an obstacle for immediate market uptake but nevertheless suggested that simultaneous improvements and the upcoming progress on low-power electronics could represent a significant opportunity for these devices. In 1977, Karube *et al*. reported on the performance of a biochemical fuel cell, employing immobilised *Clostridium butyricum* cells for electricity generation, thereby demonstrating for the first time the advantage of biological aggregates or biofilms, even if in this particular case the cells were artificially "glued" to the electrode [5].

The 80s was marked by the evolution of the Microbial Fuel Cell design (Diagrams available in [6]) and the understanding of the role of predominantly, synthetic mediators in MFC [7-11]. Two 'modes of operation' of bioanodes were described before the 70s. The first one was referred to as an indirect biochemical fuel cell in which the bacteria produced a compound that reacted with the electrode [4]. In the second one, termed direct biochemical fuel cell, the biological component of the anode produced a metabolite derived from the organic material which was more electrochemically active than the original compound. After almost two decades, researchers delved into the roles of mediators and their mechanisms. Under anaerobic conditions, an oxidised redox mediator can reroute electrons from the respiratory chain by entering the cell lipid membrane, intercept the electron transport chain at the appropriate redox level, become electrochemically reduced and diffuse outside the cell in its reduced form, shuttling the electrons to the surface of the electrode; this sequence of reactions is driven by a range of voltage differentials (δV), favouring the flow of electrons from the inner Krebs's cycle to the external electrode. The scientific community also adopted a blueprint from research done by Peter Bennetto and colleagues, which consisted of two chambers separated by a cation exchange membrane and neoprene gaskets on each side of the membrane [6]. Each chamber frame is fabricated with two holes in the top, one for the terminal of the electrode and the other to fill or empty the chamber. The chamber frames, the gasket and the membrane are held in place between two outer plates with studs and nuts in each corner. This design is used to date for current MFCs studies.

By the 1990's, microbial fuel cells were already being tested for the treatment of wastewater such as sewage [12, 13] and by the early 2000's, landfill leachate [14]. Habermann and Pommer [13] achieved a reduction of 35% and ~70% of total organic carbon (TOC) and chemical oxygen demand (COD) levels, respectively, in a system that had been running for 5 years and kept fed with real wastewater. TOC and COD are measurements widely used to date for water quality monitoring. TOC indicates the mg/L of organic carbon in aqueous systems, whereas COD measures the amount of oxygen needed to chemically oxidize a water sample.

1. MFCs leading to autonomy

Although 'autonomy' is now used to describe artificial intelligence, artificial life, biologically inspired robotics and practical engineering, the concept originally emerged in computer science and robotics. Despite robots being artifacts, built and programmed with human intervention, the tasks carried out with minimal human intervention in anthropocentric activities have been described as 'autonomous' processes [15].

In the field of robotics, there had been (and still are) two notions of autonomy; *computational* and *energetic* with the scientific community at the time (late 1990's) focussing almost entirely on the former. A distinction is also made between computational autonomy and automaticity in robots [16]. Automatic robots have been described as systems based on classical symbol processing operations, while autonomous robots are those that execute a pre-assigned task with the possibility to improve their performance by 'learning' from the environment, independently from the energy supply [16].

In biological systems, actions such as looking for food, involve a sort of homeostatic computation in which the actor weighs out the energy required for predatory or foraging actions versus the body's energy reserves. Actions such as avoiding predators or mating, help describe computational autonomy, in which a biological system is able to carry out an action that may or may not involve collection of energy. In robots, this then implies that the system must perform computations by processing information and carrying out a task based on this information. However, independently of the task, and similar to animals, a robot still requires energy to perform these given operations such as behaviour and decision-making process, resulting in an energy-limited, homeostatic computational autonomy.

For instance, a solar-powered robot's autonomy is greatly affected in the absence of solar radiation, and more dependent on internal energy storage (if one exists) limiting computational capability [17-20]. The need for *true* autonomy incentivised the scientific community recently towards more direct acquisition of natural energy and its translation to actual work, utilising local energy sources via novel energy management. Inspiration for this kind of research and development has come from biology, given that examples therein exhibit a perfect balance between computational and energetic autonomy, facilitating homeostasis for prolonged periods [19-23]. Practical examples in artificial systems have been reported in systems being able to estimate distance payload vs energy gain sufficiently well to prevent 'lethal' limits being reached and therefore exhibit an ability to make decisions solely based on energy reserves [19, 22, 23].

As predicted by Austin, the improvement in electronics opened up the field of MFCs, even though true energetic autonomy was still in its infancy in the early 2000's. This challenge in robots was therefore studied using Microbial Fuel Cells, which provided a compelling case for *artificial symbiosis*. Robots behaving like animals, as described above, would have a behavioural repertoire that mimics animals with respect to foraging and survival; at the same time, bacteria inside the MFCs would need carbon energy to remain viable and continue generating electricity for the robot to successfully collect the next token of food. The applications for such robots could be endless: space and underwater exploration, environmental clean-up, gardening, agriculture, sewerage maintenance, or even dealing with environmental disasters; for instance, cleaning oil spillages by utilising the hydrocarbons in the crude oil by employing hydrocarbon-utilising microorganisms (*Vibrio*, *Pseudomonas*, *Micrococcus*, *Nocardia* and *Acinetobacter*, *Methanococcus*) [24-26].

Inspired by the digestive capabilities of living organisms, and very much in pursuit of complete autonomy, *Slugbot* was developed at the Bristol Robotics Laboratory (at the time named Intelligent Autonomous Systems Lab), which was an autonomous robot designed to collect slugs in order to combust the biomass for methane generation, which would have been fed into on-board methane fuel cells for electricity generation [18] and could be used in "release & forget" missions. The robot, in the first instance, was designed to detect and collect slugs, which have high moisture content and no exoskeleton making them more suitable for the fermentation process and was going to be developed in two phases; the first phase focussed on the mechatronics for detecting and successfully collecting live slugs from muddy fields and was demonstrably successful [27].

In parallel to this development at the University of the West of England, Bristol, Stuart Wilkinson at the University of South Florida introduced *Gastrobots*, in which vegetable food-fed MFCs were used to power fully autonomous robots. [28-31] The theoretical framework of *Gastrobotics* involved food location and identification, food harvesting, maceration, ingestion, digestion, energy extraction and waste removal. The example developed by Wilkinson was named *Gastronome* [30]. It consisted of three linked toy train wagons. The first acted as the stomach with the anolyte tank, pumps, feeding and venting systems. The middle one contained 6 chemical fuel cells and their corresponding manifolds, utilising the digest from the stomach. The last one carried the oxidant tank, a stack of rechargeable batteries and the electronics.

The second phase of the Slugbot project, was going to develop the micro-combustor for methane generation and then connect this to a bank of methane fuel cells, however it was quickly realised by the team in Bristol that the task would be infeasible. The team led by Owen Holland and Chris Melhuish, consisted of roboticists like Ian Kelly, physicists, engineers like Ian Horsfield and a microbiologist, John Greenman, who was familiar with the then generally unknown Microbial Fuel Cells technology and who suggested that instead of methane fuel cells, perhaps autonomy could be explored, using MFCs; this was the start of the EcoBot programme of work, which is short for Ecological Robot.

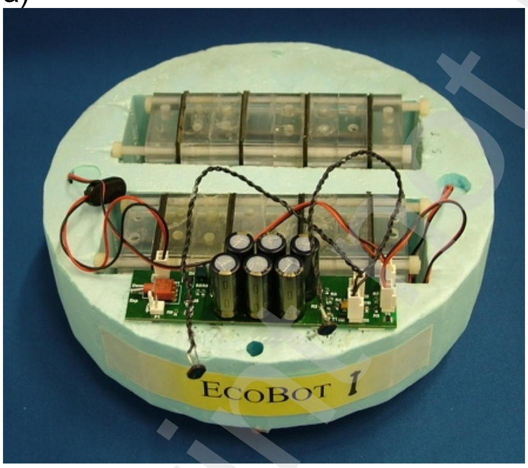
The main aim of the EcoBots was to prove the concept of energetic autonomy by using real organic substrate as the fuel for bacterial digestion and energy generation, and therefore demonstrate a kind of artificial symbiosis and consequently, feasibility. The family of EcoBots, consisting of the I, II and III generations were developed during the first decade of 21st century [32-34]. These robots employed stacks of MFCs, were manually fed and maintained in the first and second generations, and autonomously fed themselves in the third and subsequent fourth generations. The stacking method employed in the robots demonstrated the tremendous advantage of using smaller MFC units which are more power dense than large volume systems.

EcoBot I was the first compact robot to be entirely powered by bacteria for consistently repeated actuation [32]. This was a proof-of-concept photo-tactic robot consisting of eight MFCs, two photodiodes, two motors on differential drive, and an electronic circuit with six electrolytic capacitors that served as onboard energy storage/management, giving the system a duty cycle . Apart from the MFCs, there was no other source of energy powering the robot. Still inspired by nature, EcoBot I exhibited an intermittent or 'pulsed' behaviour. This meant waking up and performing work when energy was available (discharging) and going to 'sleep' mode to accumulate energy from the available food (charging) [35, 36].

The next generation of EcoBots was reported not long after. EcoBot II demonstrated the robustness and capability of MFCs to power a robot capable of phototaxis, and in addition, was the World's first to perform temperature sensing, information processing and wireless transmission of the sensed information [34]; the original robot is now on permanent display in the Bristol Museum. This second version of the EcoBot used unrefined organic matter to feed eight MFCs with an open-to-air cathode. When fed 1 fly/MFC, the robot successfully covered a distance of 50 cm in an average time of 6 hours, whilst performing the rest of its tasks effectively. EcoBot II demonstrated more effectively the notion of *artificial symbiosis*, where a microbial ecosystem and a robotic system could mutually benefit from their association [36].

As the development of the MFC technology continued, and with a view to different possible application scenarios, the first demonstration of MFCs working like artificial gills was reported in 2006 [37, 38]. MFCs with exposed cathodes, were shown to respond to increasing concentrations of aqueous oxygen, akin to how gills allow oxygen to enter the aquatic animals' bloodstream, carried by haemoglobin. This development moved away from chemical cathodes and opened up the work towards next generation terrestrial EcoBots (generation III) and the aquatic Row-Bot a few years later (see below). In parallel with this, miniaturisation of individual MFC units and their multiplication into stacks was shown to be an effective way of scaling up the technology, which then resulted in the development of EcoBot III. This robot operated successfully on sludge microbes feeding on flies and urine and employing a total of 48 small (6.25mL) volume MFCs [33]. The third generation of EcoBots addressed bio-regulation, energy management and autonomy in a much broader context. EcoBot III extended the artificial gut of the previous two generations with a circulatory system on-board and an ability to collect fresh food (ingestion), metabolise it *on the fly* (digestion) and dispose of the waste (egestion), thereby for the first time completing the thermodynamic cycle with no human intervention. The robot also collected water from its environment to cover any evaporative losses and provide aqueous oxygen to the O_2-cathodes, showing in a rather primitive way the quenching of "thirst". This involved the use of sensing and on-board actuation for keeping the internal homeostasis within an artificial environment named *EcoWorld arena*. The 48 MFCs were connected in series & parallel and assembled in 2 tiers; the overflow of the top tier MFCs flew into its downstream MFC on the bottom tier. The 'short-circuting' caused by fluid linkage was addressed with a sequential and isolated liquid distribution performed by a carousel-like, motorised mechanism also powered by the on-board MFCs [39]. Figure 1 below shows images of the three generations of EcoBots.

a)



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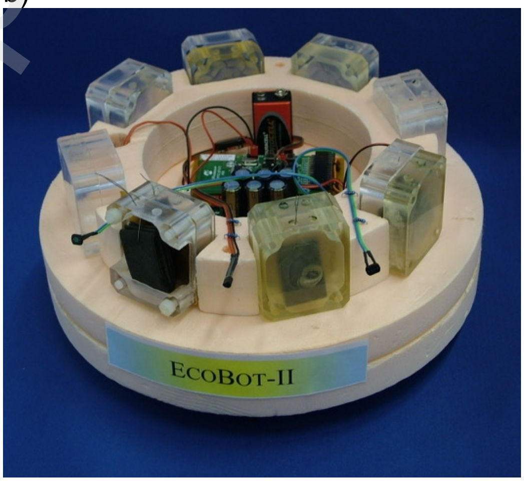

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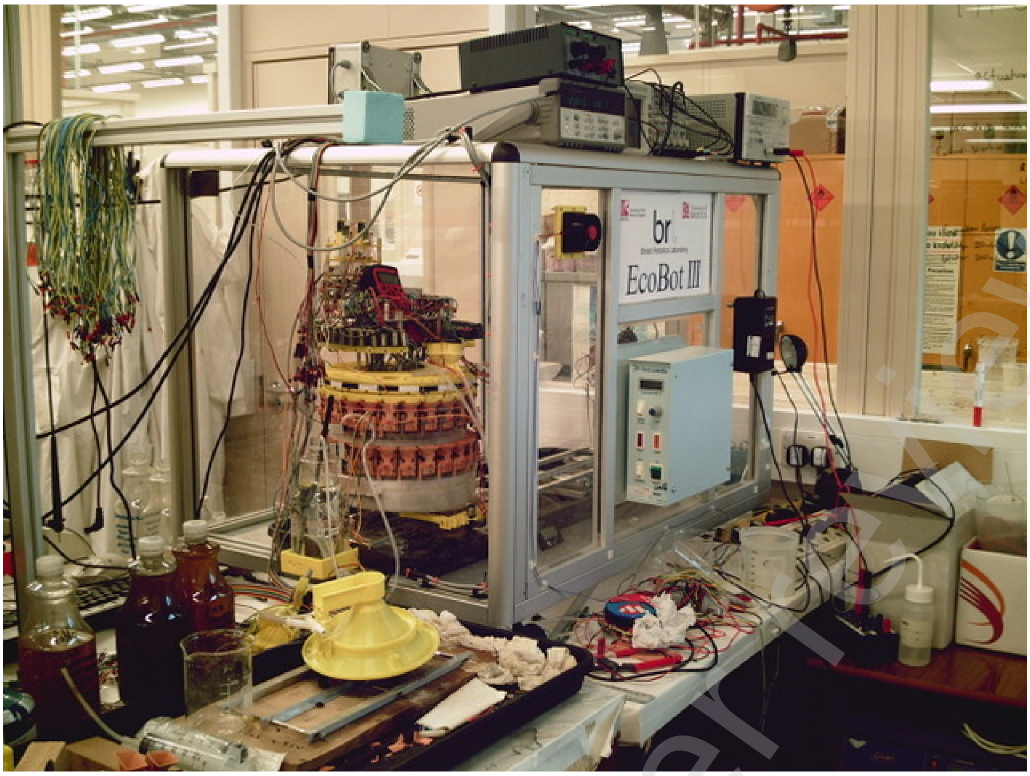

Fig 1. Family of EcoBots using Microbial Fuel Cells (MFCs) as power source. a) EcoBot I as the first exemplar of a photo-tactic robot using eight MFCs. b) EcoBot II, capable of producing phototaxis, perform temperature sensing, information processing and wireless transmission of information. c) Ecobot III using 48 MFCs and an on-board circulatory system being tested in the *EcoWorld* arena. [Images courtesy of Ioannis A. Ieropoulos]

The work towards bio-inspired autonomous robotics using MFCs continued as Philamore and colleagues published *Row-Bot* [40]. This consisted of a swimming robot, inspired by the water boatman beetle, using the liquid in its aqueous environment to feed an artificial stomach made of two MFCs. The combination of two subsystems, energy production and actuation, made possible the energetic autonomy of this robot. The design and compliant body included a side-paddling propulsion mechanism, two fed-batch cuboid MFC and mouth opening in the anterior and posterior ends, to allow fresh liquid intake, pushing out the existing spent liquid/digest. The environment where its operation was demonstrated was an acetate-based paddle, resembling artificial wastewater, as a carbon source to simulate a contaminated or blooming pond.

The development in MFCs for robotics, led to important engineering breakthroughs and scientific discoveries that informed the advancement of the technology and its scale-up for real world applications. It was during this discovery phase that fresh human urine was tested for the first time in the world as fuel for electricity generation – a discovery that opened up a whole new area of sanitation research [41]. The development in MFCs for robotics, led to important engineering breakthroughs and scientific discoveries that informed the advancement of the technology and its scale-up for real world applications. It was during this development phase that fresh human urine was tested for the first time in the world as fuel for direct electricity generation – a discovery that opened up a whole new area of sanitation research [41]. The idea was conceived during a discussion with Dr Andy Shuttleworth, a talented microbiologist serving in defence at the time, who understood the challenges faced by forward operating bases and indeed the dismounted soldier. The discussion led to the design of the first urine experiments, which made use of existing MFCs that had been running continuously, in 2010, for 2 years[1] and provided an excellent testbed with long-term, stable baseline [29]

2. Unconventional source of electricity: Urine-fed MFCs

Throughout history, animal and food waste (e.g. manure, rotten fruits) have been transformed into valuable products and services, including biogas, biofuels and less so, local electricity production. Nevertheless, this is often accompanied by complex and sometimes costly infrastructure. Developing countries often lack the appropriate infrastructure for sanitation or energy generation, resulting in poor living conditions, deprived of the very basics, taken for granted in more developed economies; this poses significant health risks leading to unnecessary mortality [42, 43]. An affordable and decentralized system that can treat human waste and convert it into useful byproducts or services regardless of location or environment, could help reduce health risks and improve the quality of life in low-to-medium income countries (LMICs).

Improvements in the raw materials of MFCs made their production more accessible by introducing free-standing cylindrical ceramics that double up as ion exchange membranes and as the chassis for the cathode and anode [44-46]. The reduction of costs allowed for the MFCs to be further exploited in the sanitation context .

In 2015, the integration of the MFC technology with toilets was piloted on two different occasions to evaluate the modular stacks of MFCs for electricity generation, assess the efficacy of urine treatment, and demonstrate the utility for indoor lighting. The studies were funded by Bill & Melinda Gates Foundation and Oxfam (grant no. OPP1094890) to potentially incorporate MFC toilets in refugee camps in disaster areas.

The first trial was conducted on Frenchay Campus, at the University of the West of England for three months, between March and June 2015. The *Oxfam Pee Power Urinal* consisted of eight modules connected in series, using 288 MFCs, retrofitted under 2 plastic urinal units. The urinal bowls directly fed the MFC modules, which in turn powered LED lighting fitted in the ceiling of the toilet cubicle. During this period, the daily volume processed was 2.5-5 L per day from 5 -10 users per day. The maximum power generated was 0.4 W for 75 hours. Additionally, 90% of the COD was reduced, with a maximum of 98%, due to relatively long hydraulic retention time (HRT).

The same eight modules from the Frenchay campus unit plus four new ones were used in the field trial at the Glastonbury Music Festival, in June 2015. The working capacity was 300 litres running continuously, accommodating thousands of users per day. The lighting system was recharged during the day and used overnight with stable power performance throughout the festival. The peak power output was equivalent to 19.2 W h for 24 h, proving the MFC-based technology a sustainable solution to improve sanitation and provide electricity at individual and community levels

The successful trial at Glastonbury led to the installation of the system for four more consecutive festivals in a collaboration between the Bristol BioEnergy Centre and the Glastonbury Music Festival; these were in 2016, 2017 and 2019 (2018 being the fallow year).

[1] This same set of MFCs is still running at the time of submitting this article, in the Environmental Labs of the University of Southampton, UK and has completed nearly 17 years (16 years and 5 months) of continuous operation [unpublished data].

The PEE POWER® urinal II used in Glastonbury 2016 was scaled up to accommodate 18 users at any given time. It was tested for 3 weeks using self-stratifying membraneless MFCs (SSM-MFC), instead of ceramic cylinder membrane MFCs [47]. The COD removal capacity improved and produced about 30% more energy with a third of the total volumetric footprint. The power density of the 2016 field trial was improved by 331% compared the 2015 set up (2.45 W m^{-3} and 0.74 W m^{-3}, respectively). The legal maximum discharge concentration in the European Union for mg COD·L^{-1} and mg TN·L−1 The PEE POWER® II urinal II used in Glastonbury 2016 was scaled up to accommodate 18 users at any given time. It was tested for 3 weeks using self-stratifying membraneless MFCs (SSM-MFC), instead of ceramic cylinder membrane MFCs [47]. The COD removal capacity improved and produced about 30% more energy with a third of the total volumetric footprint. The power density of the 2016 field trial was improved by 331% compared the 2015 set up (2.45 W m^{-3} and 0.74 W m^{-3}, respectively); the overall energy produced during the festival in 2019 was 288Wh. The legal maximum discharge concentration in the European Union for mg COD·L^{-1} and mg TN·L−1 was not yet met, nevertheless, the spent urine was in a much closer condition for direct discharge [47, 48]. For instance, urine alone contains around 75% of nitrogen found in domestic wastewater [49]. Compared to industry standards, which correspond to 92% COD and 20% TN reduction [50], the COD% and TN% removal from PEE POWER® II urinal were 88% COD and 29% TN reduction.

Although the quality of treated urine was yet to be improved, other scale-up limitations like voltage reversal or space management were successfully overcome. Voltage reversal, a common phenomenon when multiple MFC units are connected in series, was avoided by using series/parallel combinations and ensuring uniformity in the collective. On the other hand, the membrane-less MFCs usually face scale-up limitations due to the position of the cathode, which is parallel to the liquid/air interface. The SSM-MFC solved the surface area footprint limitation of the reactors. When using SSM-MFC, the position of the cathode is perpendicular to the electrolyte/air interface allowing the surface area of the electrode to increase whilst keeping the volume of electrolyte. The vertical arrangement of the cathodes also favours a natural stratification behaviour, both biological and chemical, according to the conditions that surround the microbiome at different heights in the MFCs.

The third trial at the music festival in 2017 consisted of 12 cascades with two modules each and had a capacity for 40 users using the same type of MFCs as the last year, SSM-MFC. The stack of cascades was fed through 4 of the 12 available troughs, which resulted in underperformance due to a nonhomogeneous distribution between the cascades. During the same year, an overseas Pee Power installation was commissioned at the Seseme girls' secondary school in Uganda. The ceramic MFC modules were installed adjacent to a 4-cubicle toilet block to power lights in the toilets for the first time. Similarly, in 2018, a second overseas installation took place at the Brainhouse Academy in Nairobi, Kenya, which brought light to the toilets that have never been previously illuminated.

Based on previous field trials at the Glastonbury festival, laboratory studies were made to develop a reliable system to provide illumination according to European standards without an energy management circuit for 40 people at a time [51]. After the laboratory investigations, two stacks were tested and operated for 6 days at the Glastonbury Festival in 2019 [51]. The stacks were able to power the lighting system 20 hours after inoculation. The LEDs acted as a power management system when connected directly to the SSM-MFC stacks demonstrating for the first time that MFC technology is suitable as a direct energy source in decentralised areas, such as refugee camps. Based on previous field trials at the Glastonbury festival, laboratory studies were conducted to develop a reliable system to provide illumination according to European standards without an energy management circuit for 40 people at a time [51]. After the laboratory investigations, two stacks were tested and operated for 6 days at the Glastonbury Festival in 2019 [51]. The stacks were able to power the lighting system 20 hours after inoculation. The LEDs acted as a power management system when connected directly to the SSM-MFC stacks demonstrating for the first time that MFC technology is suitable as a direct energy source in decentralised areas, such as refugee camps.

In 2019, another Pee Power system was installed in an informal settlement community in Durban, South Africa. This system lit four LED lights inside a toilet block over a period of 6 months and formed part of the Bill & Melinda Gates Foundation, Engineering Field Testing platform for technology evaluation. The modular design included 440 small-scale ceramic MFCs arranged in 4 cascades of 5 modules each and a total capacity of approximately 24L. The system produced power ranging between 3.5-5 W/m^3 (unpublished data).

The Microbial Fuel Cell technology had advanced significantly over the period of approximately 18 years (up until October 2019), both in terms of reactor form factor and power output. The graph in Figure 2 below shows the relationship between power vs reactor size and uses real data from the lab experiments that were setup during early 2002 (i.e., when the MFC EcoBot work started) up until late 2019[2], when the graph was put together for the purposes of understanding this important, inverse relationship.

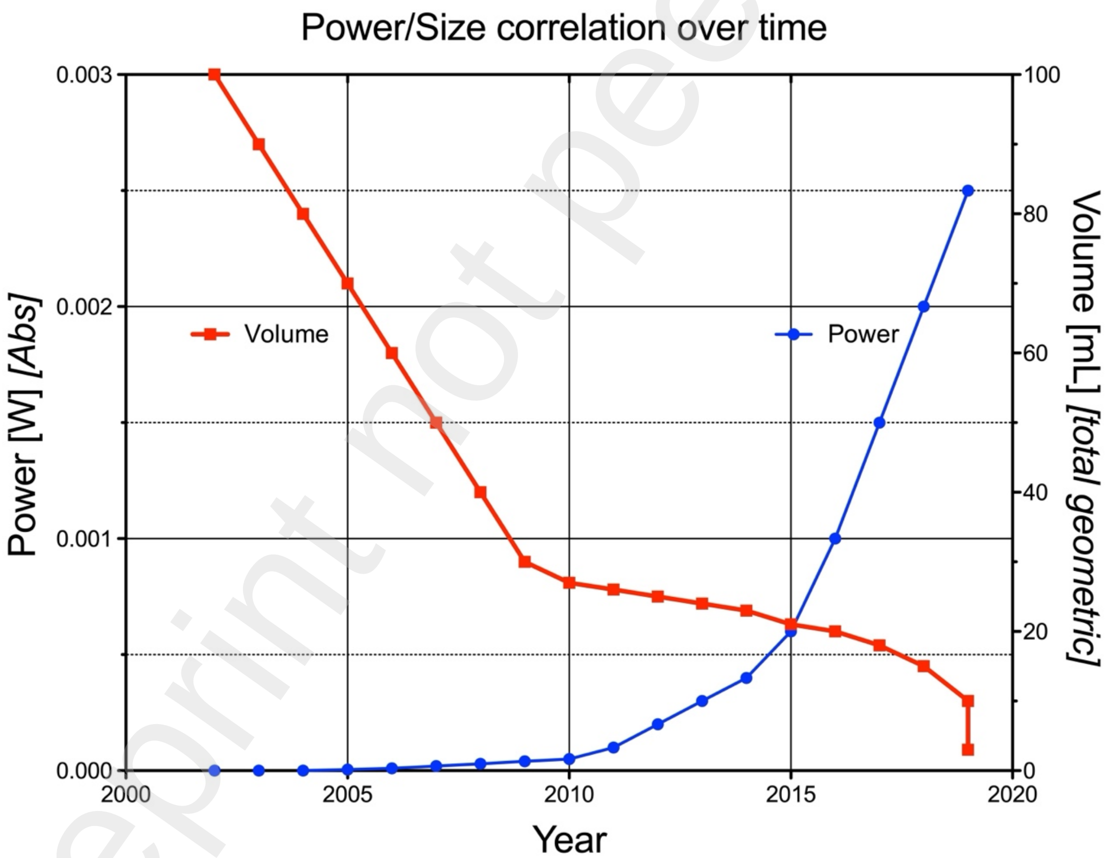

Fig 2. Power in absolute terms (Watts) versus MFC size mL. Data shown were produced from real experiments conducted with the different MFC bioreactor designs that were fabricated as part of the

[2] This graph was prepared as part of the Urinetricity (Pee Power®) technology debrief and presented at the Gates Foundation Headquarters in Seattle, October 2019.

fundamental research into bioelectrochemical systems, between January 2002 and October 2019. The last two data points show the same amount of absolute power generated from two different bioreactor sizes, 10mL and 3.6mL, which clearly illustrates the advantage of the smaller vs larger reactors.

3. Environmental monitoring using MFCs

As worldwide anthropogenic activity increased, research for new water quality monitoring methods is becoming increasingly more popular. Traditional water quality analyses are mostly based on complex analytical methods and are conducted offline in well-equipped laboratories. Thus, MFC based sensors had been proposed, in the last decade, as a low-cost technology that provides on-site monitoring of one of the most important parameters of water quality, biological oxygen demand (BOD).

Before 2010, MFCs were used as self-sustainable power supplies that used local resources to run electrochemical, temperature or pH sensors and their respective telemetry system for wireless transmission of data collected by the sensors to remote receivers [52, 53]. Not long after, the MFC were not only powering the electronics of the sensors but being the sensor itself, in a way behaving like a "living sensor" by converting biological responses to external stimuli to electrical signals associated to those stimuli.

The anodic biofilms of the MFC were shown to be sensitive and reliable when exposed to feedstock conditions different to the maturation substrates [54]. When feedstock conditions return to the original maturing substrate, they return to their previous power output levels. These studies supported the possibility of using MFC as sensor in the applications context where the system is constantly exposed to different substrates of varied natures.

Later in 2017, a novel self-powered device for online water quality monitoring using MFC technology was published [55]. This biosensor would indicate the presence of urine in freshwater by turning ON sound and light cues. The frequency of the signal coming from the biosensor was correlated to the concentration of urine present. This sensor operated autonomously for 5 months and was envisaged as an early warning system for water contamination.

More recently, in 2024, three low-cost MFC sensors were built for deployment in a local Parish Council, along one of the rivers close to the University of Southampton, to monitor its quality (data not published). The Parish Council and village in the south of England, relies on the river for various recreational activities such as paddle boarding, kayaking and wild swimming. Users reporting concerns about the water quality in the area prompted the local council and the local activity centre to look for ways of assessing pollution in the river. As part of a coordinated approach, identical "twins" were setup in the Environmental Laboratories of the University of Southampton, in order to assess the sensitivity and response time of the MFC sensors, again with sodium acetate used to simulate organic pollution in concentrations ranging from 20-100 mM. These data were also used for calibration of the MFC sensor "twin" that was then deployed in the river. During the 3 month rigorous trial (at the time of submitting this article, the sensor was still in the river logging data, after 6 months) the data from the MFC sensor showed instances where the voltage under load increased to levels above the pre-set threshold (0.3V), which corresponded to organic load concentrations of >80mM. The instances of voltage spikes coincided with heavy rainfall weather events (often a cause of combined sewer overflow – CSO) but also corroborated with aquatic macroinvertebrate population and *E. coli* monitoring, to help substantiate the data by assessing the impact of the pollutants to aquatic life. The increased voltage in the MFC sensor corresponded to a decrease in invertebrate population and increase in *E. coli* numbers, indicating bad water quality (data not published). The MFC proved to be a useful on-site monitoring tool for water quality. Although the data logging device used in the study was battery-powered, MFC can serve, not only as a sensor, but as an energy source for data logging devices in future developments. Figure 3 below is a visual representation of the main achievements in MFCs over the last 228 years.

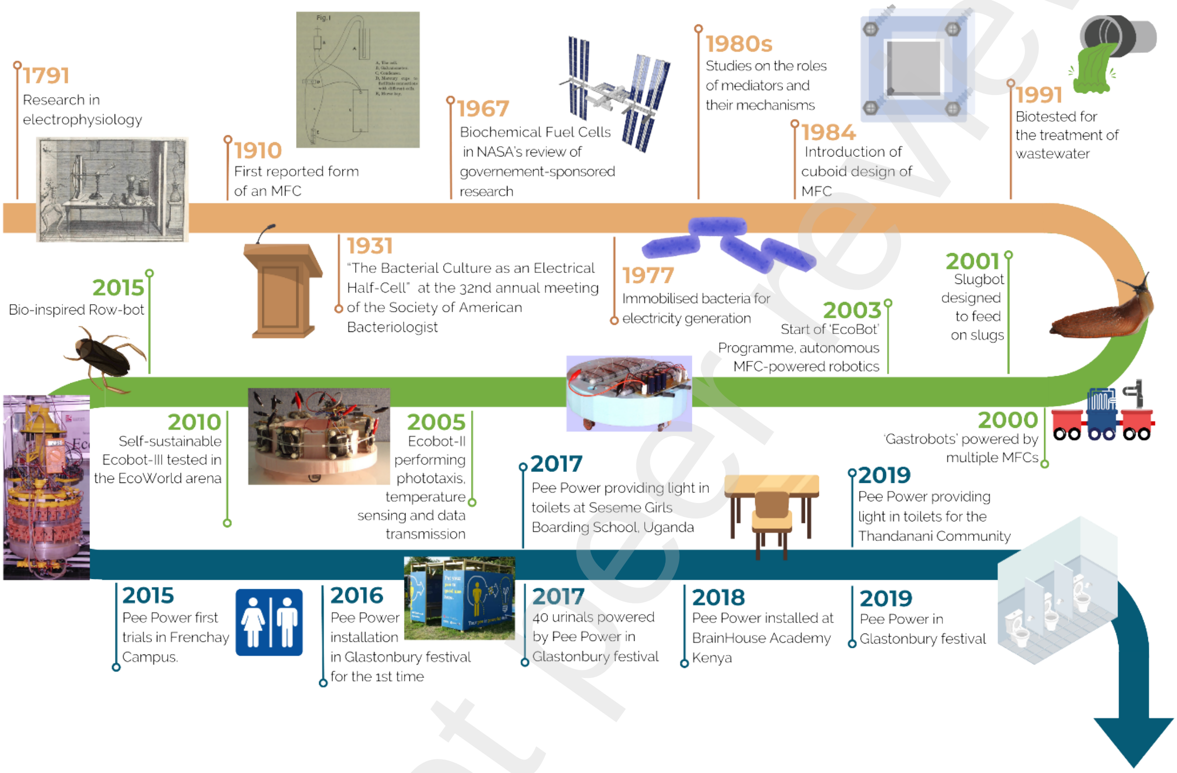

Fig 3. History of Microbial Fuel Cells development for practical applications. (1791-image courtesy of the Smithsonian Libraries and Archives [1]; 1910-image used with permission of The Royal Society (U.K.), from [2], permission conveyed through Copyright Clearance Center, Inc of the Royal Society; 2010- and 2016- images courtesy of Ioannis A. Ieropoulos)

4. MFCs for the future – space exploration

As predicted by Austin, MFCs are becoming quite the choice for crewed space explorations, and there is already a good body of literature on the topic of plants, closed-loop biospheres and microorganisms in space in general, but also on the role that biomass based fuel cells can play in extraterrestrial missions [56-64]. The lunar regolith has become the topic of rigorous studies to assess its suitability for infrastructure and structural support [65], naturally asking questions about its fertility or capacity to support microbial viability. MELiSSA is perhaps the longest running project investigating all aspects of life support in a closed loop environment and it is along such great initiatives that projects like BEATRICE are now beginning to investigate more closely specific eco-cycles in an otherwise closed system [66]. In particular, BEATRICE is studying the feasibility of coupling MFCs with their byproducts (electricity, nutrient-balanced fertiliser) and microgreens, as a local human waste treatment system that provides lighting and food in a safe and healthy manner. The prospect of utilising the remarkable capabilities of microbes for bio-transformation and *total recycling* offers countless opportunities for repairing our earthly environment and supporting sustainability beyond.

Conclusions

Just like all other technologies that have reached the consumer via a market route, MFCs were originally conceived in a different context (*vis.* animal electricity), and with different objectives. But, precisely like other examples, MFCs are continuously demonstrating value in aspects not previously anticipated, gradually finding their way as a utility of service for humans in need or for damaged environments and soils. Successful products or services must make financial sense (classic cost-benefit analysis question) but the motives behind this question often go beyond the benevolent societal gain. This is when speed to get something out on the market regardless of wider (negative) impacts, comes first and to the cost of up-and-coming biotechnologies governed by a circadian rhythm. Humanity's rate of environmental destruction is simply faster than nature's rates of processing. Bioelectrochemical Systems, of which the most advanced and diverse is the Microbial Fuel Cell, presents a bio-hybrid where the living and the artificial can be engineered to have the same circadian rhythm and offer value society. Imagine a future where friendly service robots look after our gardens, gutters, allotments, household waste and city wide sewerage, our dwellings are off-grid, yet fully self-sustainable with real-time electricity generated on-site and our society is capable of transforming most of the biomass into useful fuels and fertilisers, all through the metabolic actions of little mighty microbes.

Acknowledgments

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documented in a timely manner and the kettle was always ready for a cup of fresh tea or coffee.

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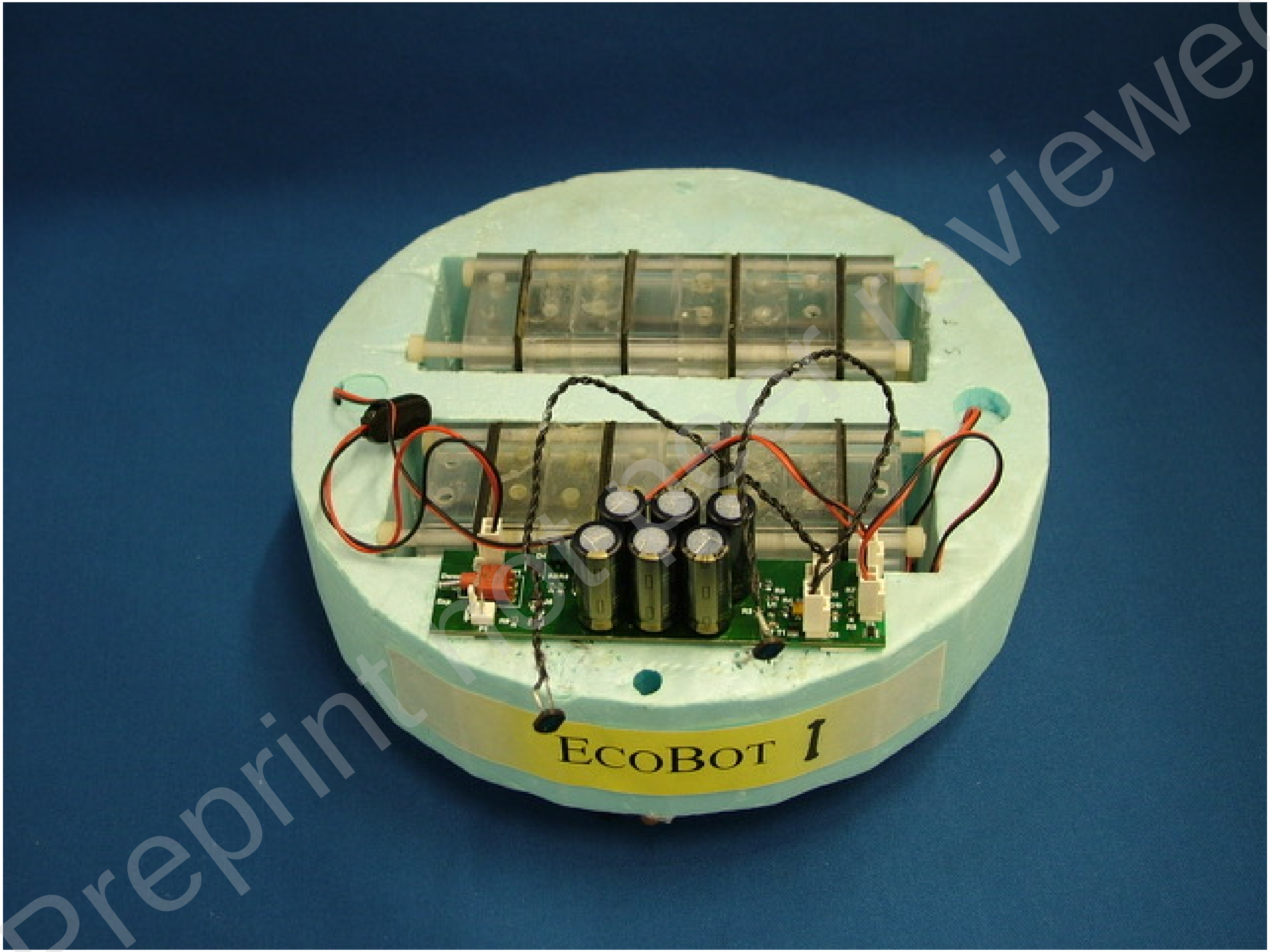
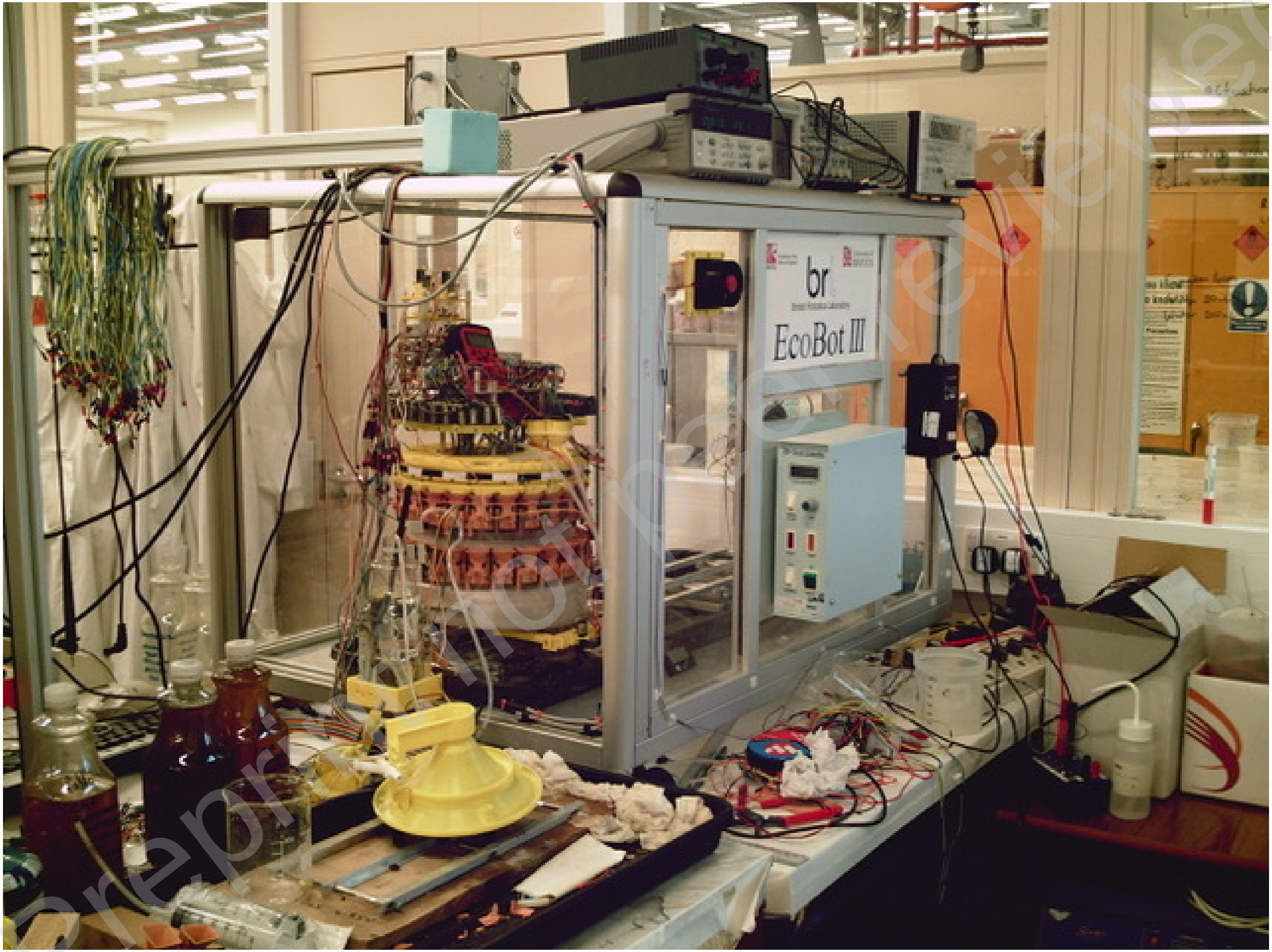
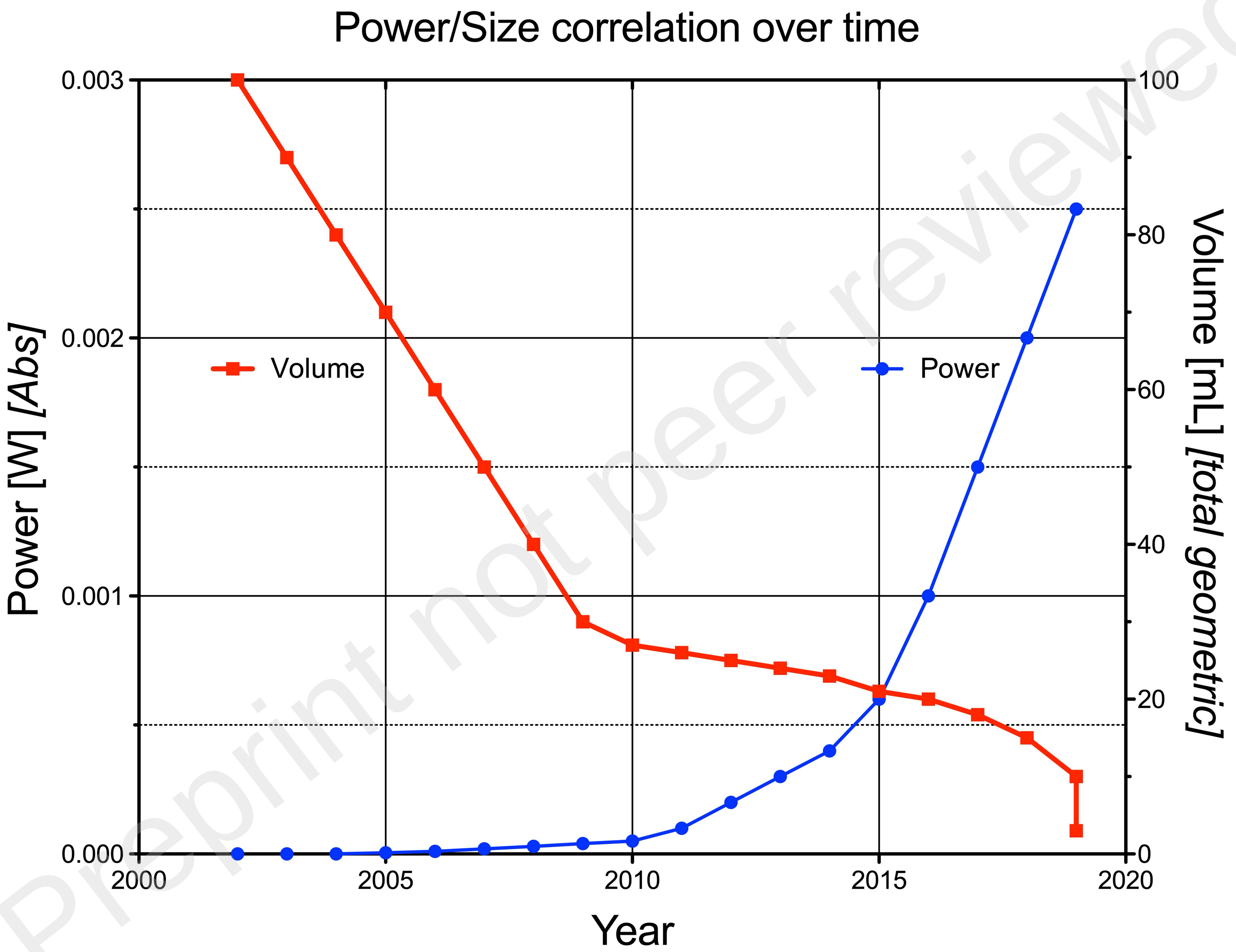
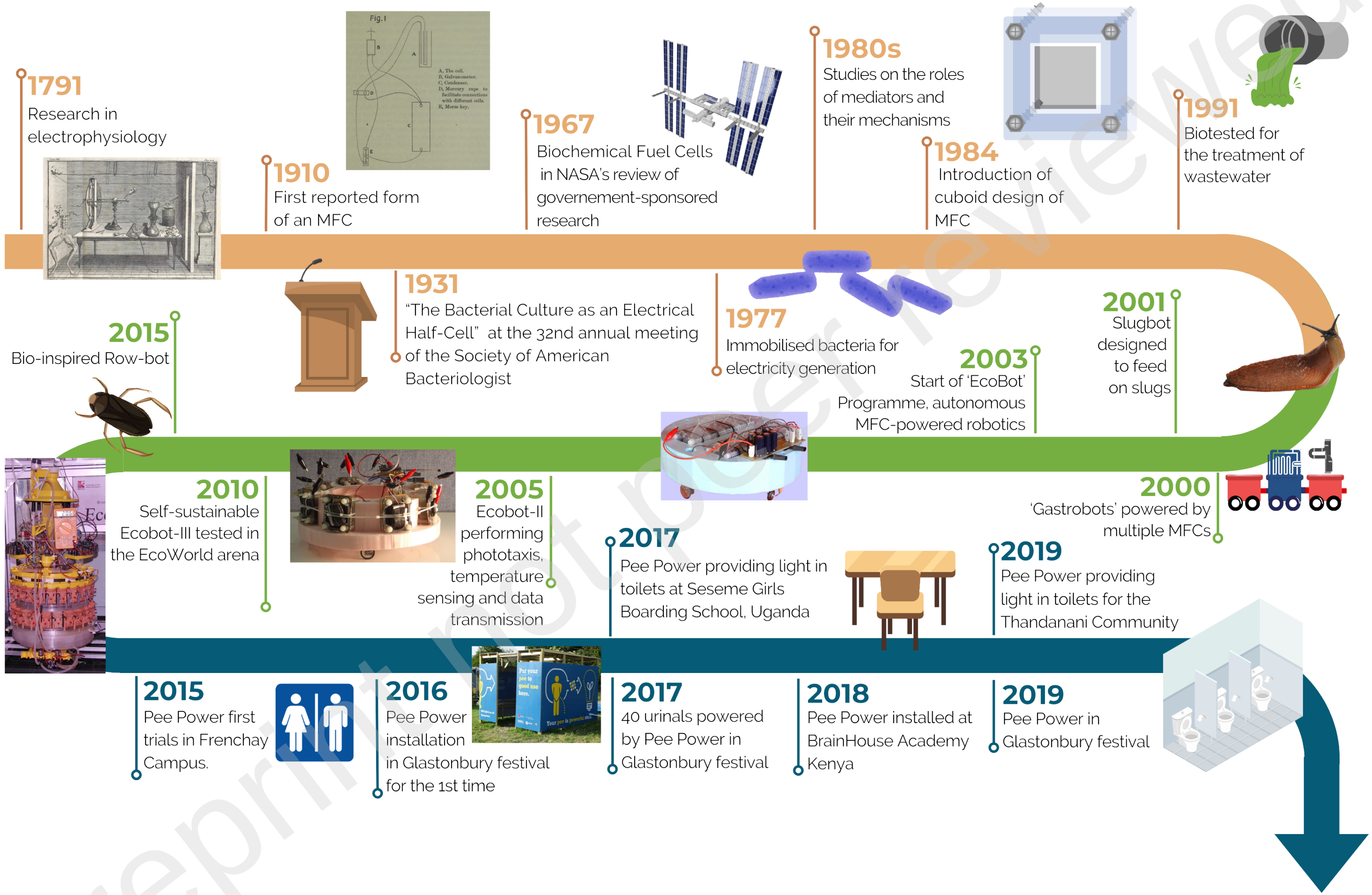

ECOBOT I


EcoBot-II


brl
EcoBot III



Power/Size correlation over time
0.003
0.002
0.001
0.000
2000
2005
2010
2015
2020
100
80
60
40
20
0
Volume
Power
Power [W] [Abs]
Volume [mL] [total geometric]
Year


1791
Research in electrophysiology
1910
First reported form of an MFC
Fig. I
1967
Biochemical Fuel Cells in NASA's review of governement-sponsored research
1980s
Studies on the roles of mediators and their mechanisms
1984
Introduction of cuboid design of MFC
1991
Biotested for the treatment of wastewater
1931
"The Bacterial Culture as an Electrical Half-Cell" at the 32nd annual meeting of the Society of American Bacteriologist
1977
Immobilised bacteria for electricity generation
2001
Slugbot designed to feed on slugs
2003
Start of 'EcoBot' Programme, autonomous MFC-powered robotics
2015
Bio-inspired Row-bot
2000
'Gastrobots' powered by multiple MFCs
2005
Ecobot-II performing phototaxis, temperature sensing and data transmission
2010
Self-sustainable Ecobot-III tested in the EcoWorld arena
2017
Pee Power providing light in toilets at Seseme Girls Boarding School, Uganda
2019
Pee Power providing light in toilets for the Thandanani Community
2015
Pee Power first trials in Frenchay Campus.
2016
Pee Power installation in Glastonbury festival for the 1st time
2017
40 urinals powered by Pee Power in Glastonbury festival
2018
Pee Power installed at BrainHouse Academy Kenya
2019
Pee Power in Glastonbury festival