2011 Trends in Biotechnology Microbial solar cells: applying photosynthetic and electrochemically active organisms. David P.B.T.B. Strik, Ruud A. Timmers, Marjolein Helder, Kirsten J.J. Steinbusch, Hubertus V.M. Hamelers, , Cees J.N. Buisman. Trends in Biotechnology 29 (1), 41-49

Abstract

Microbial solar cells (MSCs) are recently developed technologies utilizing solar energy to produce electricity or chemicals. MSCs use photoautotrophic microorganisms or higher plants to harvest solar energy, and use electrochemically active microorganisms in the bioelectrochemical system to generate electrical current. Here, we review the principles and performance of various MSCs, in an effort to identify the most promising systems as well as the bottlenecks and potential solutions towards ‘real life’ MSC application. We give an outlook on future applications based on the intrinsic advantages of MSCs, showcasing specifically how these living energy systems can facilitate the development of an electricity-producing green roof.

Background

Society is facing local and global challenges to secure the needs of people and planet [1, 2]. One of those needs is energy, which should be available in the form of electricity or fuels, ideally produced from a renewable source via an efficient and clean conversion process. The microbial solar cell (MSC) is a new collective name of biotechnological systems that integrate photosynthetic and electrochemically active organisms to generate *in situ* “green” electricity or chemical compounds, such as hydrogen, methane, ethanol and hydrogen peroxide [3-5]. MSC is a recent development that builds on the discovery of electrochemically active bacteria and subsequent development of microbial fuel cells (MFCs) [6-10]. The MFC typically cleans wastewater and generates electricity from organic compounds present. Within the MFC, electrochemically active bacteria at the anode oxidize organic compounds and deliver electrons to the anode. These electrons flow through a power harvester to the cathode, where electrons are delivered to reduce oxygen [11]. In a MSC, the photosynthetic organisms use sunlight to produce organic matter that is further converted into electricity using the MFC [9, 12, 13]. The most investigated MSC is the plant microbial fuel cell (PMFC), which has a living plant that delivers organic matter via its roots to electrochemically active bacteria in the MFC [12, 14-19].

Our aim is to review the principles and performance of MSCs, presenting the challenges and the outlook for future applications of these technologies. Various MSCs have been recently described, which can be categorized according to the way solar energy is captured and the mode of organic matter transfer from the photosynthetic portion to the fuel cell. Both reported and potential performance of the different MSCs are analyzed to recognize bottlenecks and to identify solutions. Currently, it is not possible to predict the cost-effectiveness of the technology; however based on the known advantages of MSC technology, potential applications and tradeoff with other renewable energy generation technologies are discussed.

Principles and performance of microbial solar cells

The basic principles of MSCs, as illustrated in figure 1, are: (i) photosynthesis; (ii) transport of organic matter to the anode compartment; (iii) anodic oxidation of organic matter by electrochemically active bacteria; and (iv) cathodic reduction of generally oxygen. We have categorized the MSCs below according to the way solar energy is captured and the mode of organic matter transfer: the higher plant with rhizodeposition (PMFC); the phototrophic biofilm with diffusion; and the photobioreactor or coastal marine ecosystem, which use pumps for translocation. The in-depth bio-electrochemical principles of all systems are yet to be fully revealed [3, 7, 12, 20-26]. Table 1 gives an overview of recent developments on MSC performance and efficiency.

Plant microbial fuel cell

MSCs with living higher plants are called plant microbial fuel cells (PMFCs) [12]. With PMFCs, the plant’s roots directly fuel the electrochemically active bacteria at the anode by excreting rhizodeposits [12, 14-19]. Rhizodeposition of plant roots is the excretion of organic compounds into the soil, including sugars, organic acids, polymeric carbohydrates, enzymes and dead-cell material. The rhizodeposits account for approximately 20–40% of the plant’s photosynthetic productivity, and these compounds can be degraded by a mixture of microorganisms [25]. When the plant is growing with its roots in the MFC, electricity is continuously generated *in situ*. The first published PMFC study estimated that 21 GJ/ha/year (67 mW/m^2) net power generation is theoretically possible under Western European (i.e. Netherlands, Belgium, France) climate conditions[12]. This net yield is on par with conventional biomass electricity production systems, including digestion of energy crops which achieve net power generation of 2.8 to 70 GJ/ha/year (based on: biogas production of 160-400 GJ CH_4/ha/year[27]; gas combustion efficiency of 25%[28]; and energy input of 30%[29]) and biomass combustion which achieves net power generation of 27 to 91 GJ/ha/year (based on: biomass productivity of 8–12 ton dry weight/ha/year; heating value of 18-20 GJ/ton; biomass combustion efficiency of 20-40% and energy input of 5%[30]). The theoretical power output of 21 GJ/ha/year for the PMFC is a relatively conservative estimation since a multidisciplinary European research consortium (www.plantpower.eu) estimated that the power output of the PMFC may reach 1,000 GJ/ha/year (see explanation in Box 1).

Three PMFC studies have integrated the anode in the sediment in which plants were growing [14, 15, 18]. In these studies, rhizodeposits from plants and organic matter from the sediment were available for generating a current. It was found that introduction of growing rice plants in a MFC resulted in a sevenfold increase power output as compared to the sediment MFC [14]. Outdoor experiments in Japan were also performed in a rice paddy field [15, 18]. However, in these cases, power output was not higher than reported for a sediment MFC without plants [15, 31]. The difference in power output between the rice paddy experiments and the sediment MFC experiment may be due to a variety of factors, including: the presence of rice plants, the sediment composition, the microbial species and the fuel cell design [32].

The average power density (PD) over the operation time (OT) of 33 days of the PMFC with the plant *Spartina anglica* was 50 mW/m^2. Of all reviewed varieties of MSCs, the *Spartina anglica* PMFC study achieved the highest long-term current and power density [16].

The microbial community at the anode PMFCs was analyzed to unravel the principles and performance of PMFCs. It was shown that the most common bacteria were from the families *Desulfobulbus* or *Geobacteraceae*[19] or were closely related to *Natronocella, Beijerinckiaceae, Rhizobiales* and *Rhodobacter*[15]. It has been proven that species of some of these families, like *Geobacter sulfurreducens,* are electrochemically active [33]. However, it has not been shown whether electrochemical active species were indeed present and active in a PMFC.

MSCs with phototrophic biofilms

Solar energy is converted to electricity by growing a phototrophic biofilm on the anode of the fuel cell (Table 1) [13, 21, 34-37]. These MSCs with phototrophic biofilms have self-organizing biofilm containing *Chlorophyta* and/or *Cyanophyta* and can operate for sustained periods of more than 20 days [36]. All studies to date have used mixed microbe populations, which likely includes electrochemically active bacteria. A exception is one study in which a pure culture of *Synechocystis PCC-6803* was applied to generate an electrical current [21]. This cyanobacterium is able to form electrically conductive nanowires when cultivated under carbon dioxide limitation and excess light. As such, *Synechocystis* may be used for transferring electrons from the microorganism to the anode [21, 38].

Some of the MSCs include sediment, which provides additional organic matter. One of these studies estimated that the 2.5-cm-thick marine sediment applied, contained enough organic matter to operate the system for 22 years [37]. To date, the theoretical output for a MSC with a phototrophic biofilm has not been estimated. Based on the primary carbon production of benthic biofilms of 250 g/m^2/year in The Netherlands, an MFC energy recovery of 60% and glucose as the carbon composite [39, 40], we have estimated a maximum power output of 61 mW/m^2 [36, 37]. This value is on the same order of magnitude as the PMFCs [12].

The average power density of MSCs with phototrophic biofilms was maximal 7 mW/m^2 – sevenfold lower than best PMFC and 11% of the estimated maximum of MSCs with phototrophic biofilms (Table 1) [16, 37].

MSCs with photobioreactors

MSCs can use photobioreactors to harvest solar energy via photosynthetic microorganisms like algae [21, 41-43]. Figure 2 shows an example of a MSC with a photobioreactor and an anaerobic digester. Here, the digester pre-treats the photosynthetic metabolites and microorganism before supplying them to the MFC [42]. Photobioreactors with algae can achieve PAR (photosynthetic active radiation; spectral range of solar radiation from 400 to 700 nm which can be used by micro algae for photosynthesis) photosynthetic efficiencies of 15%. With a MFC energy recovery of 29%, a power production of 2,806 mW/m^2 is theoretically possible under Western European climate conditions [41, 44]. The best results have been achieved with *Chlorella* in a photobioreactor, where a photosynthetic efficiency of 6.3% (PAR-based) was reached. With a power conversion efficiency (PCE) of 0.04% this system most effectively converted light energy into electricity of all reviewed MSCs (Table 1). This resulted in 14 mW/m^2 average power production, which was only 0.5% of the theoretical maximum [41]. It is important to note that, for the production of photosynthetic metabolites in photobioreactors, energy is needed for mixing and removing oxygen up to values of 10 W/m^2 [41]. Thus, with the current state-of-the-art, MSCs with photobioreactors will have no net electricity production.

MSCs with coastal marine ecosystem

MSCs may be integrated into the coastal marine ecosystem [45]. This ecosystem uses solar energy and produces phytoplankton like macro-algae and zooplankton that float in the ocean.

By harvesting these kinds of substrates electricity can be generated by a MFC [43, 45, 46]. In a ‘real life’ implementation, it was envisioned that pumps could be used to feed raw seawater to a 40-km-long, tubular MFC to generate electricity [45]. It has been estimated that MSCs at coastal zones, which account for 10% of the ocean, can generate electrical power of 2.4 to 16 TWh/year which is, or when divided by the surface area, 0.01-0.05 mW/m^2 [45, 47]. This power density is more than a factor 1,000-fold less than MSCs that use higher plants or phototrophic biofilms. Analysis of current state-of-the-art, estimates that the energy input is 18 times more than the electricity output [45].

Challenges towards improvement of energy recovery

Reviewing the most recent expectations for theoretical power generation and the achieved performances in the previous section, it is clear that PMFCs and phototrophic biofilms have the highest power generation (50 and 7 mW/m^2, respectively) [16, 37] and highest estimated net power potential (67 and 61 mW/m^2, respectively). This makes PMFCs and phototrophic biofilms the most promising MSC systems. Overall, MSCs are robust, with operating times in the range of 5-175 days (Table 1) [14, 36]. In contrast, other MSCs use chemical catalysts which poison the system within hours and are thus not self sustaining [48-51]. MSCs with catalysts generate fuels *in situ*, such as hydrogen, which are oxidized via conventional fuel cells.

The important question is: How can the power density be increased to obtain a cost-effective MSC? This question can not be answered yet, because all MSCs developed to date are lab-scale systems and are not designed for scale-up. In addition, insufficient and too incomplete data are available for all major processes, which precludes accurate calculations. For example, there are no measured data available on the coulombic efficiency (CE; fraction of electrons from total oxidized electron donor which are transferred to the anode) in MSCs.

Currently, it is experimentally challenging to determine the exact carbon and electron fluxes and, therefore, the CE.

However, MSC performance may be improved in pursuit of the estimated maximums, as there are many approaches possible to increase the power density. There are many parameters that determine the power density of MSCs. Some parameters are comparable to those indentified within the MFC research field and can be optimized using the same principles. For example, fuel cell performance can be improved by lowering internal resistances (IR), which are between 10 and 1800 Ω (Table 1). In the following paragraphs, we have highlighted specific MSC studies to highlight specific challenges and opportunities for improving power output.

Increase substrate flux from photosynthetic to electrochemically active organisms

It has been observed that MSCs, such as the PMFC, can be substrate-limited [16], suggesting that the anode compartment comprising electrochemically active bacteria can oxidize more organic matter (i.e. electron donors) than supplied. Thus, improving substrate flux of easily biodegradable exudates, for example via an increase of rhizodeposition, will likely enhance the overall energy recovery of the PMFC. Literature reveals several mechanisms toward enhancing rhizodeposition [52, 53]. The choice of plant plays a major role in the quantity and composition of rhizodeposits [25, 54]. The MSCs in Table 1 have current densities that are considerably lower than conventional MFCs, which achieve values up to 6.5 A/m^2 [40, 55]. Although substrate flux does not solely determine the current density, we expect from the values shown in Table 1, that several MSCs face substrate limitation. Complex substrates can become more available to electrochemically active microorganisms via pre-treatment (e.g. hydrolysis) of complex electron donors [42, 55]. In one study using an anaerobic digester and a MFC, the algae suspension was partly digested into methane and the remaining substrate was fed to the anode of the MFC [42]. Applying first a hydrolysis stage, instead of an anaerobic digestion, followed by feeding to the anode of the MFC, might make more electron donors available for electrochemically active microorganisms [42].

Improvement of substrate availability is also needed to operate MSCs for prolonged periods at the maximum PD. MFC power output can be increased by bringing the external resistance close to the internal resistance of the system [56, 57]. However, this route towards maximizing power output is only effective when substrate flux of the system is increased as well [56]. Within a PMFC, it was shown that an optimization strategy of lowering external resistance to be equal to internal resistance was unsuccessful, possibly owing to substrate limitation [16, 17]. The same study showed that, based on maximum PDs compared to average PDs, a successful maximization strategy could lead to a 10-fold increase in power output [17].

Reduce oxidation state of organic matter derived from the photosynthetic organism

MSCs use a wide variety of electron donors, including both easily biodegradable, low-molecular-weight substances as well as slowly biodegradable cellulose materials. Many of these electron donors can be converted in MFCs [58-61]. The amount of electrons that can be derived from the electron donor depends on the individual oxidation state of the substance. Therefore, by controlling the kind of electron donor mobilized by the photosynthetic organisms, and, with that, the oxidation state of the electron donor, energy recovery can be improved in the MSC. For example, several plants increase the release of low molecular weight compounds, such as sugars, amino acids and phenolics, under iron- or zinc-limitation conditions [52]. The remaining challenge is to control the plant exudation in such a way that more reduced compounds are excreted.

Increase CE of organic matter oxidation at the anode

The presence of other electron acceptors near the anode possibly negatively affects the CE of photosynthetic metabolites in MSCs. Photosynthetic metabolites may be oxidized by mixed cultures using oxygen (aerobic degradation), nitrate (nitrification), sulfate (sulfate reduction) or carbon dioxide (methanogenesis) as a final electron acceptor instead of the anode, which leads to a reduction in the CE [11, 62, 63]. An important source of alternative electron acceptors in several MSC studies are nutrient media for plants and microorganisms containing substantial amounts of alternative electron acceptors, such as nitrate and sulfate [12, 14, 16, 17]. Such electron acceptors can be replaced by more reduced components, thereby potentially increasing the CE [12, 14]. Oxygen is also a relevant alternative acceptor within PMFCs. Plant roots excrete oxygen, which can be used by the microbial population present or can produce internal currents. In the latter case, oxygen is reduced within the anode compartment while using the electrons derived from the electrochemically active bacteria present in the same anode. Hence, these electrons do not flow to the cathode which thus reduces the power output [63]. The total release of oxygen into the rhizosphere can be reduced by decreasing the average root length (e.g. using *Glyceria maxima* [12]), because oxygen introduction into the rhizosphere decreases with root length [64].

Reduce pH gradient resistance of the fuel cell

The proton production in MFCs leads to acidification in the anode compartment. Accumulation of protons creates a pH gradient over the membrane, which results in a pH gradient potential loss (i.e. the pH gradient resistance) [7, 65, 66]. This phenomenon also occurs in MSCs [13]. Acidification has been observed in a PMFC, which could be related to current generation [16]. Although the pH in the rhizosphere of the applied plants is generally slightly acidic (5-6), reducing acidification will increase the energy recovery of this and other MSCs [16]. Several measures have been proposed to reduce acidification in MFCs, which can be translated to MSCs [7, 67, 68]. However, one must pay attention to the necessary energy input, since using buffer or circulation thereof costs energy and therefore may diminishes the net power production.

Reduce transport and ionic resistance of the fuel cell

The total internal resistance of MSCs is a result of pH gradient resistance, anode resistance, cathode resistance, and ionic and transport resistance. These values have been calculated for PMFCs [16, 66]. Ionic resistance was reduced by using a salt marsh species, thereby enabling current generation at higher ionic strengths [16]. In that salt marsh species MSC study, it has been observed that transport resistance accounts for the largest fraction of the total internal resistance [16]. This was due to the fact that the anolyte was a stagnant water layer with an ion concentration gradient. This had to be overcome in order to drive cations from the anode to the cathode. Mixing of the anolyte or circulation of the catholyte over the anolyte will break down the concentration gradient of cations and anions, and thus reduce the transport resistance.

Reduce anode and cathode resistance of the fuel cell

Similar to MFCs, MSCs have a specific anode and cathode resistance that can be reduced to improve energy recovery. General approaches, like increasing the anode surface area to reduce resistance, can be derived from studies on similar bioelectrochemical systems [3, 8, 40, 69] which have been reviewed elsewhere [8][3][40], .

MSCs with oxygen reduction on graphite show poor performance because cathode resistance arises from charge and mass transfer resistance [3, 70, 71]. Mass transfer resistance can be reduced by using air-cathodes, however, long-term operation of air-cathodes may be challenging because oxygen transport could be hindered by precipitates at the electrode, as shown in bio-cathodes [72]. Cathode resistance can also be reduced by increasing the surface area of the electrode or by enriching the cathode with a biofilm (so-called 'bio-cathodes') [3, 41, 70, 73]. Bio-cathodes use populations of microorganisms or isolates that catalyze the reduction of oxygen or other electron acceptors, like manganese or iron [70, 74-77].

The charge transfer resistance can also be decreased using an electro-catalyst like platinum – a solution that has been demonstrated in several MSCs [21, 34, 43, 69]. The challenge here is to lower the dosage of costly Pt [78]. Other MSCs use ferric cyanide as a final electron acceptor; this is suitable for laboratory experiments, but not feasible for large-scale systems, as it needs frequent replenishment [69].

Reduce energy input of MSCs with photobioreactors or with coastal marine ecosystems

MSCs that use a photobioreactor or MSCs with coastal marine ecosystems require an energy input of 6-10 W/m^2 for processing the electron donor for the MFC [41-43, 46]. This energy input can diminish the net energy production of these MSCs [41, 45]. Thus, options for improving the energy input efficiency include: (i) reducing the needed energy input, and (ii) improving the photobioreactor productivity. Many valuable ideas on the improvement of photobioreactors have been published [79].

MSCs that feed the MFC with seawater from coastal marine ecosystems are limited by very dilute electron donors. These can be concentrated for higher power output [45], however, it remains to be solved how this can be achieved with lesser energy input.

Prospects and future applications

We have shown that MSC technology is advancing, with the most promising MSCs employing higher plants or phototrophic biofims. The basic principles of MSCs have been demonstrated; now it is time to improve the systems for 'real life' applications. Compared to conventional solar cells, MSCs have some attractive properties that warrant further development and will influence future applications of this technology [80]:

- MSCs can produce not only electricity, but also a wide range of fuels and chemicals; this means that energy carriers both fuels and electricity can be supplied, in contrast to solar cells which solely generate electricity [3].
- PMFCs can be easily incorporated into landscapes or into urban areas where it “greens” the city. For example, PMFCs can be combined with green roofs to create electricity-producing green roofs powering up to a third of a modern household (Box 2).
- Both the photosynthetic and electrochemical reactions are carried out by a continuously growing population of microorganisms. This makes the system capable of self-repair, conferring a longer lifetime and low maintenance.
- Another advantage of using of reproducing organisms is that there is no need for special catalysts, like Cd, that are either costly or toxic [80]. Thus the MSC can be applied in natural surroundings with no risk of pollution.
- MSCs have organic material as intermediate energy carriers between the photosynthetic and the electrochemical portions of the cell. This organic material accumulates in the MSC, therefore allowing electricity generation in the dark [12, 13, 41].
- Closed MSC systems can preserve nutrients for the organisms, which enable long-term, low-maintenance power production.
- Integrated PMFCs can add value to other applications, such as greenhouses with food or flower production, or rice paddy fields with rice production [14, 15]. Additionally, wastewater and surface water treatment can be integrated into PMFCs to supply extra organic matter for energy production [3, 12].

Currently, there are promising possibilities for application of MSCs according to the best long-term power output of 50 mW/m^2 (Table 1). Meteorological sensors for temperature, pressure and humidity installed on a buoy which requiring 24 mW were powered by a sediment MFC [81]. We expect that these sensors and other low power requiring applications like LED lights can be powered by MSCs.

Acknowledgements

This research received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement n° 226532. In addition this work was funded by SenterNovem, the Dutch governmental agency for sustainability and innovation from the Ministry of Economic Affairs (grant no. EOSLT06020) and NUON. We thank Nora Sutton, Marc Spiller, Jan Arends and the anonymous reviewers for their valuable comments on the manuscript.

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Box 1. Electricity generation potential of plant microbial fuel cells

A first estimate for the realistic electricity production of PMFC under Western European conditions was 21 GJ/ha/year (67 mW/m^2) [12]. This estimate was based on: (i) the average solar radiation of 150W/m^2 in Western Europe (e.g. Netherlands, Belgium, France); (ii) an average photosynthetic efficiency of 2.5%; (iii) a common rhizodeposition of 40%; (iv) a rhizodeposit availability for microorganisms of 30%; and (v) a microbial fuel cell energy recovery of 29%, including a growth season of 6 months [12]. This potential was according the technological state-of-the-art in 2008, using general data on the conceptual process steps of the PMFC.

In 2010, a PMFC using *Spartina anglica* reported a long-term power generation of 50 mW/m^2 [16]. Extrapolating these results to a 6 month growth season, 25 mW/m^2 could be produced on a yearly basis, accounting for 37% of the estimated maximum. Today, a multidisciplinary European research consortium (www.plantpower.eu) is working towards an optimal electricity production of 1,000 GJ/ha/year (3.2 W/m^2). This value is based on the highest reported data of the conceptual process steps. With an average solar radiation of 150 MW/km^2 in Western Europe [82], increased photosynthetic efficiency of 5% [24], a majority (70%) of photosynthates transported to the soil [83], and a possible 60% energy recovery by the MFC [40] of these photosynthates, the 3.2 W/m^2 power output would be possible.

For application in natural conditions, it was expected that 50% (1.6 W/m^2) can be harvested. Of course, it is recognized that these numbers are all dependent on the system constituents, the environmental conditions, and time course of the experiment. Moreover, challenges mentioned in this review have to be surmounted. Nevertheless, it shows that there is room for optimization to achieve higher power output. The primary challenge is to further understand the principle processes of PMFCs in order to subsequently design and operate

PMFCs with higher power outputs. With further knowledge, mechanistic models can provide future estimates of power generation [84].

Box 2. The electricity-producing green roof

One of the most promising applications for the PMFC is the green roof, because it can combine the advantages of these roofs with electricity generation by the PMFC. Green roofs are implemented all over the world, especially in cities, and offer a myriad of advantages: (i) storm-water run-off retention; (ii) high aesthetical value; (iii) increased biodiversity; (iv) air-quality improvement; (v) building insulation; and (vi) urban heat island mitigation (reduction of temperature within cities which have higher temperatures than rural surrounding areas) [9, 10, 85]. When applying a PMFC on these green roofs, decentralized electricity production can be added to these advantages. On a flat roof of 50 m^2 – a reasonably sized roof in the Netherlands – 150 W could be continuously produced when the proposed maximum of 3,2 W/m^2 is reached (see Box 1). Assuming an average electricity need of 500 W [86] the green roof could provide about one-third of the household's electricity need. It can be expected, though, since energy use of the household will decrease thanks to the insulation capacity of the green roof, the PMFC power would account for a larger share of households energy need. At an electricity price of 0.25 €/kWh, a 50-m^2 electricity-producing green roof could potentially save a household € 330 per year.

To integrate the PMFC with a green roof, several bottlenecks still have to be overcome. As the plants in a PMFC need to be submerged, water retention on the green roof becomes more important. Consequently, the weight of the roof will increase, which might require a fortified building construction. Moreover, current laboratory set-ups are built with a lot of materials, leading to high costs associated with a scaled-up system. Detailed design of the electricity producing green roof is therefore very important as it will determine both the weight and the costs of the system. The current state of this technology does not enable us to propose a specific design yet. Regardless of the challenges, the integration of the PMFC with a green roof offers the opportunity of producing electricity at the consumer, while improving the quality of the urban environment.

Box 3: Trade-off between PMFCs, wind turbines, and solar panels

Focusing primarily on energy production, the use of PMFCs or phototrophic biofilms may be an alternative for photovoltaic solar panels or wind turbines to create energy-producing landscapes. As opposed to other alternative renewable electricity sources, PMFCs offer the opportunity to increase both the aesthetic value and the biodiversity of such landscapes. However, photovoltaic solar panels and wind turbines can achieve higher power yields; thus, a cost-benefit analysis is required when considering implementation of a renewable electricity technology [87].

When applied in a natural environment, PMFC power yield is estimated at a maximum of 1.6 MW/km^2 (Box 1). Whereas wind turbines could generate 5-7.7 MW/km^2 on a typical wind farm in Europe [88]; solar panels could generate 4.5-7.5 MW/km^2 under Western European conditions (solar radiation: 150W/m^2; PCE: 15-25%; tilted position of solar panel thus uses 2.5 m^2 land per m^2 solar panel) [80]. In summary, power output of wind farms and solar farms will be 3-5-fold higher than that of PMFCs. With an increasing need for electricity and in light of the European political goal of generating 20% of its energy-need in 2020 from renewable sources, pressure on high-energy-yield per surface area is increasing [89]. At the same time, however, environmental impact of both wind turbines (avian mortality, visual impacts, noise, electromagnetic interference) and solar panels (visual impacts, loss of green space and biodiversity, increasing dark surface, use of polluting metals) is large and is a source of societal debate [80, 89]. PMFCs could offer an opportunity for electricity generation while sustaining the natural environment at locations where windturbines or solar panels are not desirable. Future integration of PMFCs into closed systems could provide 24 hour per day electricity generation, without the use of scarce materials and with nutrient preservation.

Table 1. Performances and efficiencies of MSCs

Category MSC	**Photosynthetic organism(s)**	**Electron donor(s)**	**Microbial community**	**OT (days)**	**CDavg*a* (mA/m2)**	**CDmax*a* (mA/m2)**	**PDavg.*a* (mW/m2)**	**PDmax*a* (mW/m2)**	**CE (%)**	**IR (Ω)**	**PCE (%)**	**Electron acceptor(s) (catalyst)**	**Refs.**
Plant	*Glyceria maxima*	Rhizodeposits	Bacteria	67	32	153	4	67	-	525	0.01	Oxygen	[12]
Plant	*Oryza sativa ssp. indica*	Rhizodeposits	*Desulfobulus* cluster *Geobacteraceae* *Archaea*	134	44	-	21	33	31	-	0.004	Ferricyanide	[14, 19]
Plant	*Spartina anglica*	Rhizodeposits	Bacteria	78	141	-	22	79	-	1800	0.01	Oxygen	[16]
Plant	*Spartina anglica*	Rhizodeposits	Bacteria	33	214	-	50	100	-	750	0.01	Ferricyanide	[16]
Plant	*Arundinella donax*	Rhizodeposits	Bacteria	112	-	-	10	22	-	-	0.001	Oxygen or ferricyanide	[17]
Plant	*Spartina anglica*	Rhizodeposits	Bacteria	154	-	-	21	222	-	-	0.001	Oxygen or ferricyanide	[17]
Plant	*Oryza sativa ssp. indica*	Rhizodeposits, Potting soil	*Desulfobulus* *Geobacteraceae* *Archaea*	175	120	-	26	-	-	-	-	Ferricyanide or oxygen (bacteria)	[14, 19]
Plant	*Oryza sativa L. cv.Sasanishiki*	Rhizodeposits Rice paddy soil	*Natronocella* *Beijerinckiaceae* *Rhizobiales*	120	-	52	-	6	-	156	-	Oxygen	[15]
Plant	*Oryza sativa L. cv.Satojiman*	Rhizodeposits Rice paddy soil	Bacteria	-	-	163	-	14	-	-	-	Oxygen (Pt)	[18]
Phototro-phic biofilm	Filamentous *Cyanophyta* *Chlorophyta*	Metabolites of photosynthetic microorganism	Filamentous *Cyanophyta* *Chlorophyta*	8	-	115	-	5.9	-	10	-	Oxygen (Pt)	[34]
Phototro-phic biofilm	Filamentous *Cyanophyta* *Chlorophyta*	Metabolites of photosynthetic microorganism	Filamentous *Cyanophyta* *Chlorophyta*	20	-	5	-	0.2	-	212	-	Oxygen (Pt)	[21]
Phototro-phic biofilm	*Cyanophyta* *Chlorophyta*	Metabolites of photosynthetic microorganism	*Cyanophyta* *Chlorophyta* *Trinema* Bacteria	22	6	105	2	41	-	102	0.001	Ferricyanide or oxygen (bacteria)	[13]
Phototro-phic biofilm	*Chlorophyta*	Metabolites of photosynthetic microorganism	Bacteriodetes *Chlorophyta* *Alphaproteobacteria* *Betaproteobacteria*	9	40	86	0.3	84	-	1300	-	Oxygen (Pt)	[35]
Phototro-phic biofilm	*Cyanophyta* *Chlorophyta*	Metabolites of photosynthetic microorganism	-	5	-	0.3	-	0.001	-	-	-	Oxygen	[36]
Phototro-phic biofilm	*Cyanophyta* *Chlorophyta*	Metabolites of photosynthetic microorganism and/or sediment	*Cyanophyta* *Chlorophyta* Bacteria	> 20	-	13	-	1.4	-	-	-	Oxygen	[36]
Phototro-phic biofilm	*Chlorophyta*	Metabolites of photosynthetic microorganism and/or sediment	*Chlorophyta*	> 7	48	96	7	14	-	-	-	Oxygen	[37]
Phototrophic biofilm	*Synechaocystis PCC-6803*	Metabolites of *Synechaocystis PCC-6803*	*Synechaocystis PCC-6803*	18	-	5	-	0.5	-	343	-	Oxygen (Pt)	[21]
Photobio-reactor	*Chlorella*	Metabolites of *Chlorella*	Bacteria *Chlorella*	161	77	210	14	110	3	33	0.04	Ferricyanide	[41]
Photobio-reactor Digester	*Chlorella*	Effluent of digested micro algae	*Chlorella*	58	2	26	0.1	1	40	-	-	Oxygen	[42]
Photobio-reactor^b	*Chlorella vulgaris*	*Chlorella vulgaris*	Bacteria	5	-	2500*c*	-	980 *c*	10-30	-	-	Oxygen (Pt)	[43]

		composite											
Coastal marine ecosystem	Phytoplankton	Metabolites of phytoplankton and zooplankton	*Proteobacteria flavobacterium Bacteroides*	50	-	328 *c*	-	17 *c*	14	-	-	-	[46]
Coastal marine ecosystem**	*Ulva lactuca*	*Ulva lactuca* composite	Bacteria	7	-	2000 *c*	-	760 *c*	7-20	-	-	Oxygen (Pt)	[43]

*a*Geometric photosynthetic surface area (m2).

[b] Electron donor was produced external.

*c*Geometric anode electrode surface area (m2).

Figure captions

Figure 1. Model of the microbial solar cells cell including the basic principles: (i) photosynthesis ($6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$); (ii) transport of organic matter to the anode compartment; (iii) anodic oxidation of organic matter by electrochemically active bacteria (e.g. $C_6H_{12}O_6 + 12\ H_2O \rightarrow 6\ HCO_3^- + 30\ H^+ + 24\ e^-$); and (iv) cathodic reduction of oxygen to water ($6\ O_2 + 24\ H^+ + 24\ e^- \rightarrow 12\ H_2O$).

Figure 2. Schematic overview of a closed loop concept of a MSC with photobioreactor and digester (Reprint with permission of John Wiley and Sons) [42]; (i) photosynthesis by micro algae takes place in the photobioreactor; (ii) biogas is produced from organic matter which is transported from the photobioreactor to the digester; (iii) in the anode of the MFC the remaining organic matter, which is transported from the digester to the anode, is oxidized by electrochemically active bacteria; (v) in the cathode of the MFC oxygen, which is transported from the photobioreactor to the cathode, is reduced to water.

Figure 1

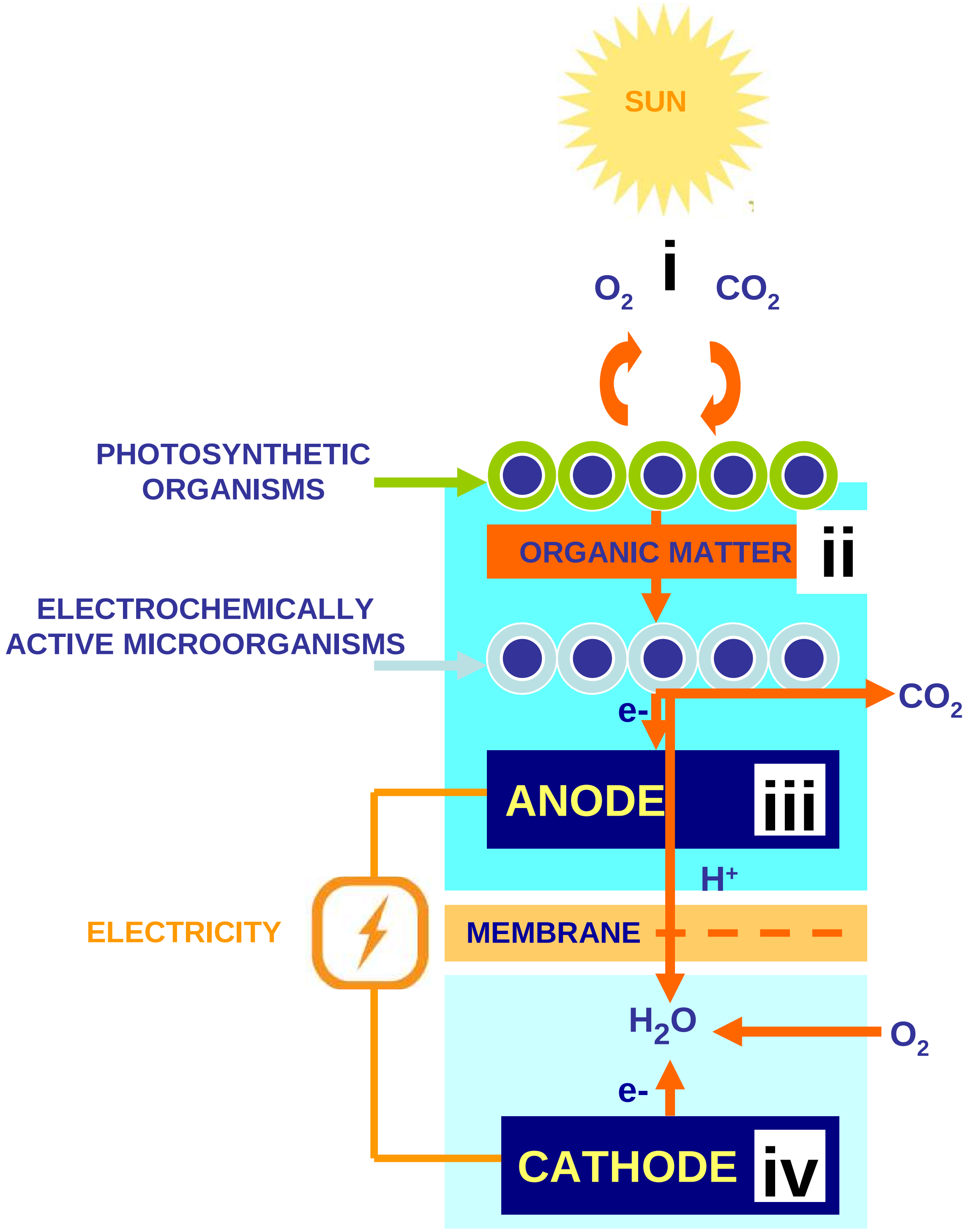
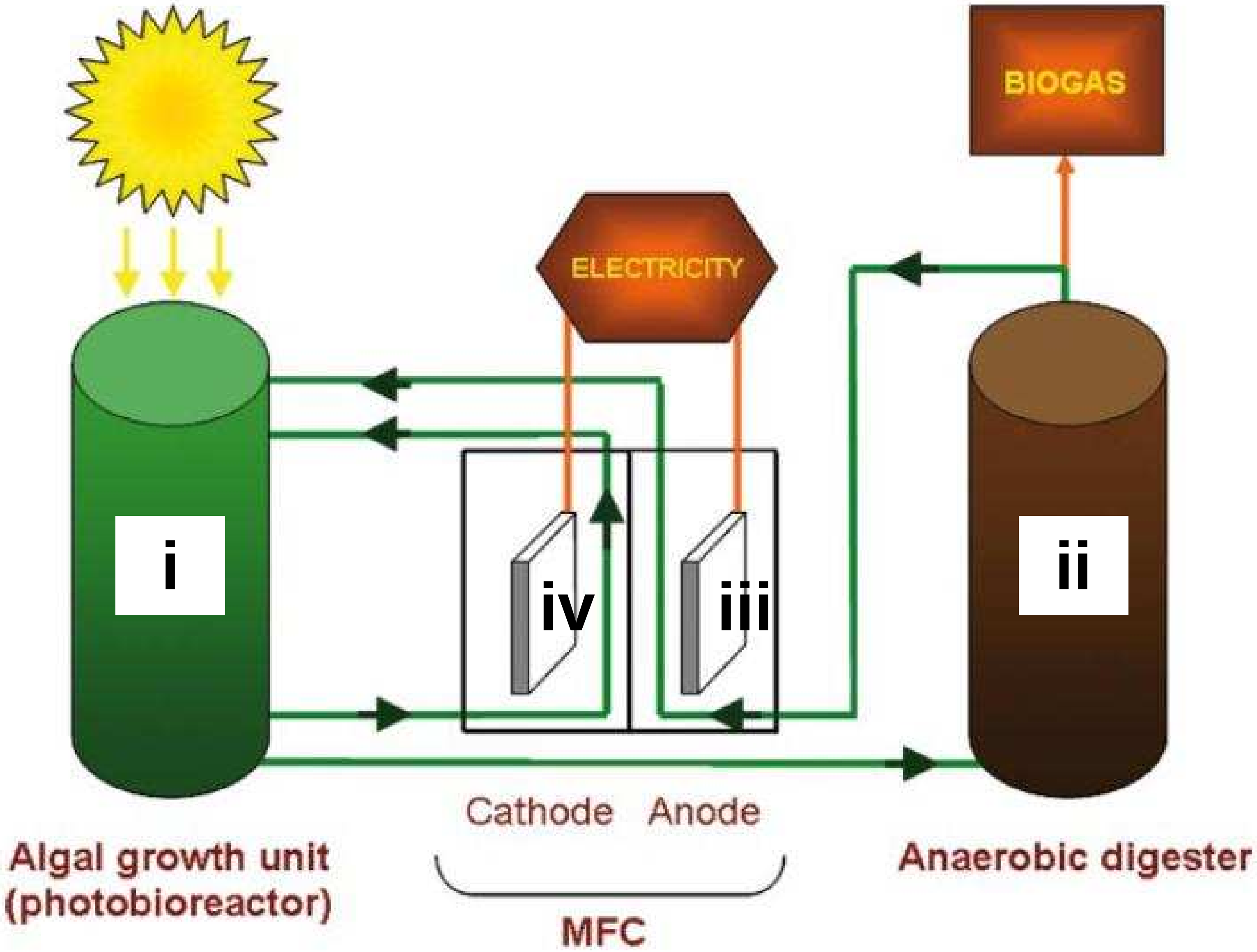

SUN
i
O_2
CO_2
PHOTOSYNTHETIC ORGANISMS
ORGANIC MATTER
ii
ELECTROCHEMICALLY ACTIVE MICROORGANISMS
CO_2
e-
ANODE
iii
H^+
ELECTRICITY
MEMBRANE
H_2O
O_2
e-
CATHODE
iv

Figure 2


BIOGAS
ELECTRICITY
i
iv
iii
ii
Cathode
Anode
Algal growth unit
(photobioreactor)
MFC
Anaerobic digester