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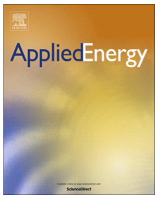

Microbial electrolysis cells for hydrogen production and urban wastewater treatment: A case study of Saudi Arabia

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HIGHLIGHTS

- KSA is the world's third largest per capita water user country.
- 1.17 (domestic), 0.38 (industrial) billion m^3/year wastewater is generated in KSA.
- 612, 767 MW electricity can be produced for years 2025, 2035 from wastewater by MEC.
- Net 508, 637 MW electricity for years 2025 and 2035 can be added to national grid.
- MEC technology can achieve 25.6% of KSA 3G W electricity from waste target by 2035.

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ABSTRACT

This paper reviews the status of microbial electrolysis cells (MEC) as a mean for hydrogen (H_2) production and urban wastewater treatment method. A case study of the Kingdom of Saudi Arabia (KSA) under MEC concept was developed. KSA is the world's third largest per capita water user country with no lakes and rivers. Every year, around 1.17 and 0.38 billion m^3 of domestic and industrial wastewater is generated respectively. The KSA government is seeking sustainable solutions for wastewater treatment and waste-to-energy (WTE) production to bridge the ever increasing water and energy demand-supply gap. However, there is no WTE facility exists to convert the wastewater into energy. Moreover, the potential of wastewater is not examined as an energy recovery substrate. This study, for the first time, estimated that a total electricity of 434 MWe can be produced in 2015 from the KSA's wastewater if MEC technology is employed. Similarly, an estimated total electricity of 612 and 767 MWe can be produced for the years 2025 and 2035 from the domestic and industrial wastewater by using MEC technology. A surplus electricity of 508 and 637 MWe for the years 2025 and 2035 respectively can be added to the national grid after fulfilling the energy requirement of MEC wastewater treatment plants. Collectively, MEC will contribute 20.4% and 25.6% share of the KSA government's WTE target of 3G W in 2025 and 2035 respectively. A number of challenges in MEC such as ohmic and concentration losses, saturation kinetics and competing reactions that lower the H_2 production are discussed with their potential solutions including, the improvements in MEC design and the use of appropriate electrolytes, antibiotics and air or oxygen.

1. Introduction

Today, the world is facing the challenges of energy crisis and clean water shortage. In 2005, the global energy consumption was 460 quadrillions BTUs (British thermal units) that is expected to increase by 57% till 2030 [1]. Currently, the fossil fuels are the most exploited energy sources (up to 90%) in the world that are not only depleting the natural resources, but also damaging the environment and changing our climate [2]. Since last two decades,

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Abbreviations: BES, Bioelectrochemical Systems; BTUs, British Thermal Units; CH_4, Methane; COD, Chemical Oxygen Demand; CO_2, Carbon Dioxide; GW, Gigawatts; H_2, Hydrogen; KACARE, King Abdullah City of Atomic and Renewable Energy; KSA, Kingdom of Saudi Arabia; LCA, Life Cycle Assessment; MEC, Microbial Electrolysis Cell; MFC, Microbial Fuel Cell; MW, Mega Watts; NO_x, Nitrous Oxide; O_2, Oxygen; Pt, Platinum; VFA, Volatile Fatty Acids; WTE, Waste-to-Energy.

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the renewable energy production has gained significant attention due to technological advancement, reduced process cost and governmental subsidies [3]. The conventions like Kyoto protocol and agenda 21 are also forcing the fossil fuel based economies towards renewable energy based economies [4].

The wastewater generation is increasing significantly worldwide due to ever growing urbanization and population, particularly in developing countries [3]. Currently, about 90% of generated wastewater in developing countries is discharged to rivers, oceans and lakes untreated [5]. Annually, 6–8 million people die from waterborne diseases; of which around 1.8 million are children under the age of 5 years [6]. Moreover, the methane (CH_4) and nitrous oxide (NO_x) emissions from wastewater have negative impact on climate and their levels are estimated to increase by 50 and 25% respectively by 2020 [5,6]. The conventional wastewater treatment processes are energy intensive; typically consuming around 3% of the total electricity produced in many developed countries [7]. Therefore, improving urban wastewater services with new technologies is an imperative need of the time for achieving sustainability in wastewater treatment sector.

The hydrogen (H_2) production from wastewater is a promising way of treating wastewater and producing renewable energy. H_2 is a non-toxic and highly inflammable gas with high calorific value (~142 kJ/g) (Table 1). Globally, around 500 billion m^3 of H_2 is produced every year with 10% growth rate [10] from natural gas (40%), heavy oils and naphtha (30%), coal (18%), electrolysis (4%) and biomass (1%) [11]. The produced H_2 is used in ammonia production (49%), petroleum refining (37%), methanol production (8%), and in various minor applications (6%) [12]. A number of techniques are available for H_2 production such as water splitting, coal gasification and natural gas reforming but most of these are not feasible for large scale production due to high electricity cost or excessive carbon dioxide (CO_2) emissions [13]. However, in recent years, the H_2 productions from biological processes such as direct and indirect photolysis, photo and dark fermentation and microbial electrolysis cell (MEC) using renewable resources are gaining significant attention due to reduced catalytic cost and process energy demands [11]. However, the efficiency of these processes varies with the substrate type, process mechanism, end products and energy input [14].

Table 1
Physical and technical properties of H_2 [8,9].

Properties	Values
Gas density	0.08 kg m^{-3}
Boiling point	20.3 K
Heat of vaporization (ΔH_{vap})	444 kJ kg^{-1}
Flammability range	4–75% (in air)
Liquid density	71 kg m^{-3}
Lower heating value (mass)	120 MJ kg^{-1}
Lower heating value (liquid, volume)	8960 MJ m^{-3}
Diffusivity in air	0.63 cm^2 s^{-1}
Ignition temperature in air	585 °C
Ignition energy	0.02 MJ
Flame velocity	270 cm s^{-1}

MEC is a novel technique for H_2 production that uses domestic and industrial wastewater as a substrate through the catalytic action of microorganisms in the presence of electric current and absence of oxygen (O_2). The H_2 production rates are significantly higher in MECs (80–100%) in comparison to the fermentation process and water electrolysis (Table 2). Moreover, the threshold potential required in MECs is much smaller than that required for conventional water electrolysis (1.23 V) [23]. The phototrophic conversion of organic substrate to H_2 by algae and photosynthetic bacteria due to low solar efficiencies and large surface area requirements could not generate higher energy than MEC, which is 90% at the rate of 0.5 kW h/m^3-H_2 [24–26].

KSA and Gulf nation's governments are seeking sustainable solutions for wastewater services, including its treatment and energy recovery and the use of treated wastewater as a viable source to bridge the ever increasing water and energy demand-supply gap [2,4]. In Gulf region, neither such waste-to-energy (WTE) facility exists to convert wastewater into energy, nor is the potential of wastewater examined as an energy recovery substrate [27–32]. However, in order to build such a demonstration plant, an assessment study is critical with strong commitment from all stakeholders, including government, public, policy and decision-makers and business investors [33–35]. In this regard, the current study will make a foundation by demonstrating the possibilities and potential of a suitable WTE technology based on the local wastewater composition and generation rates. The paper examines the potential of MEC technology for urban wastewater treatment and renewable energy production in KSA. The study provides an extensive literature review on the status of MEC technology development to date, challenges to overcome yet, potential solutions for overall process optimization and an assessment of the potential electricity generation in KSA from MEC technology as a case study.

2. Microbial Electrolysis Cell (MEC)

MEC is rapidly growing bioelectrochemical system (BES), wherein an electrochemical process takes place under the influence of biological catalyst to generate energy by utilizing a wide range of substrates [36]. MECs are the advanced version of microbial fuel cells (MFCs) that utilize bacteria to break down organic substrates [37]. They are almost similar to our modern day batteries having anode and cathode [36]. There are single and double chambered MECs to produce H_2 from a wide range of substrates (Fig. 1). However, single chambered membrane-less MECs are more economical to achieve high H_2 production rates [38]. A five-fold increase in H_2 production was reported by Tartakovsky et al. [39] in a continuous flow membrane-less MEC. In addition to single

Table 2
Comparison of the energy parameters of different techniques used for H_2 production.

Systems	Energy efficiency (%)	Potential for energy generation (kJ/L)		References
		Domestic	Industrial	
MEC	90% 0.5 kW h/m^3-H_2	7.6	16.8	[13,15–17]
Pyrolysis	35–55% (500–700 °C)	2.95–4.64	6.5–10.2	[18]
Fermentation	33%	2.78	6.16	[19,20]
Water Electrolysis	65% 4.5–5 kW h/m^3-H_2	5.48	12.1	[21]
Hydro-power coupled to alkaline electrolysers	60–65%	5.06–5.48	11.2–12.13	[22]
Nuclear reactors coupled with thermochemical cycles	40–43%	3.4–3.6	7.5–8.02	[22]

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