Fuel 381 (2025) 133642

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Review article

Photoelectrocatalytic water splitting for efficient hydrogen production: A strategic review

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ARTICLE INFO

Keywords:
Hydrogen
Photoelectrocatalysis
Solar energy
Advanced oxidation process
Photoelectrode

ABSTRACT

Hydrogen generation via water splitting is the most captivating one, out of the different technologies employed for its production, owing to the abundance of the essential raw material (water) on our planet. Photoelectrocatalysis (PEC), which combines two powerful advanced oxidation processes, viz., photocatalysis and electrocatalysis, has the potential to use solar energy to split water into Oxygen and Hydrogen at ambient temperature and pressure. This article is a strategic review that discusses the ingenious techniques for increasing the overall efficiency of a PEC process for the purpose of Hydrogen production via water splitting. It analyses the various schemes and parameters of electrode engineering, electrolyte effects and cell architecture. The principal emphasis is on skilled photoelectrode development and process intensification by synergistic operations. This review provides a reference for a comparative study of novel developments and new directions in PEC for the production of Hydrogen, thus encouraging propitious research and rewarding commercialization.

1. Introduction

1.1. Statistics and concerns

Global energy demand, fuelled by climatic and economic security concerns, has resulted in the emergence and acceleration of the renewable era. Global annual renewable energy investment increased in 2022 and has continued in 2024 [1]. The escalation of climate security concerns has prompted a reduction in the utilization of conventional sources of energy. Global coal demand, for instance, is projected to increase marginally through 2025 before rapidly declining to the point where it is 25 % lower in 2050 compared to 2020 [2,3].

Recognizing the demand for fuels with low emissions, efforts are underway to develop low-carbon Hydrogen strategies [4]. As per an International Energy Agency (IEA) report [2], the net zero scenario of low-carbon Hydrogen and Hydrogen-based fuel demand in 2030 would be close to 18 EJ. According to a recent report [5], the combined worldwide demand for Hydrogen across various sectors including power, transportation, ammonia-fuel, synfuel, construction, and grid infusions is estimated to be around 210 Mt (Fig. 1). The production of Hydrogen through water splitting, aided by solar energy, contributes to the Net-Zero Emissions Scenario, 2050, by minimizing carbon footprints [5–7].

Of the several Hydrogen-producing processes (Fig. 2), the solar water splitting technique [8–12] is gaining impetus, owing to its low-carbon footprint discharge and strong sustainability.

Photoelectrocatalysis (PEC), an advanced oxidation process (AOP) based on photocatalysis and electrocatalysis, is a technique of splitting water through the utilization of solar radiation. It has the advantage of thriving on entities that are freely and abundantly available in nature, namely, water and solar energy and needs no toxic handling. Nonetheless, certain characteristics still need to be addressed for feasible scale-up and active commercialization.

Excellent review articles are extant on various aspects of PEC, viz., antimicrobial effects of PEC [14], mineralization of drugs [15], nanomaterials in PEC [16], progress in PEC [17], PEC for wastewater treatment [18], upcycling of plastic waste via PEC [19], PEC for oxidation of alcohols [20], etc. In the present article, an in-depth analysis and review of the two niche criteria of PEC functionalization has been attempted, viz., strategic photoelectrode material engineering for subsequent reduced charge carrier recombination, and process intensification of PEC by synergizing it with other operations, which drastically enhances its overall Solar to Hydrogen (STH) efficiency. A detailed SWOC analysis of the current status of PEC for functional commercialization is also presented, which should serve as gaps and a guiding light for further

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https://doi.org/10.1016/j.fuel.2024.133642
Received 6 August 2024; Received in revised form 7 October 2024; Accepted 4 November 2024
Available online 13 November 2024
0016-2361/