INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–12

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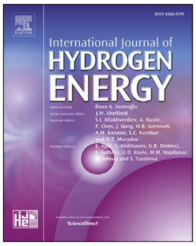

Hydrogen concentrator demonstrator module with 19.8% solar-to-hydrogen conversion efficiency according to the higher heating value

Arne Fallisch [a,*], *Leon Schellhase* [a], *Jan Fresko* [a], *Mario Zedda* [a], *Jens Ohlmann* [a], *Marc Steiner* [a], *Armin Bösch* [a], *Lukas Zielke* [b], *Simon Thiele* [b], *Frank Dimroth* [a], *Tom Smolinka* [a]

[a] *Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstrasse 2, 79110 Freiburg, Germany*
[b] *Department of Microsystem Engineering - IMTEK, Georg-Köhler-Strasse 105, 79110 Freiburg, Germany*

ARTICLE INFO

Article history:
Received 5 May 2017
Received in revised form
5 July 2017
Accepted 8 July 2017
Available online xxx

Keywords:
Solar hydrogen production
PEM water electrolysis
III-V solar cells

ABSTRACT

Renewable hydrogen is a key element to a sustainable energy system of the future. Therefore solar hydrogen generation has been investigated by various research groups in recent years. The patented concept of the Hydrogen Concentrator (HyCon), which combines III-V multi-junction solar cells with polymer electrolyte membrane electrolysis, has been constantly developed over the last years. In this work, a unique weatherproof HyCon module with an area of 8 × 90.7 cm^2 was build and characterized in an outdoor measurement for over two month. During this measurement period, the module showed a stable operation regardless of the water volume flow. The module works under natural convection without any circulation pumps at a suitable maximum temperature of 60–70 °C. The HyCon module consists of eight individual units (HyCon cells), each combining a photovoltaic and an electrolysis cell. Some of the HyCon cells reach a solar-to-hydrogen conversion efficiency of 20% according to the higher heating value at high current densities of 0.8 A/cm^2. On the module level a maximum efficiency of 19.8% is reached. To the best of our knowledge this is the highest conversion efficiency so far achieved at such high current densities using a dual junction solar cell.

Introduction

As is commonly known, fluctuating renewable energies must be stored in order to achieve an energy system which is running independent from fossil fuels like coal and oil. Hydrogen, which is applicable as long term storage, has shown a huge potential to fulfill these needs. Therefore renewable hydrogen is a key element to a sustainable energy system of the future.

To convert energy transmitted by the sun to the earth into hydrogen different approaches exist. One approach is a decoupled system where a photovoltaic (PV) module or field is connected via power electronics to an electrolyzer unit [1,2]. Such a system has the advantage that each component can be optimized on its own. The power is only stored if it is needed, otherwise the power can be used directly. On the down side, the thermal waste heat of the PV cannot be used and power electronics lead to additional power losses and costs.

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[*] *Corresponding author.*
E-mail address: arne.fallisch@ise.fraunhofer.de (A. Fallisch).

http://dx.doi.org/10.1016/j.ijhydene.2017.07.069

Please cite this article in press as: Fallisch A, et al., Hydrogen concentrator demonstrator module with 19.8% solar-to-hydrogen conversion efficiency according to the higher heating value, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.07.069

Furthermore, the electrical interconnections of the solar cells as well as the interconnection of the PV modules to power the electrolyzer unit induce further power losses and add up to the total investment costs.

In another approach the solar cell is in direct contact with water. Thus the electrochemical reaction directly takes place at the surface of the solar cell. This concept is often referred to as photo-electric cell (PEC) or "artificial leaf" due to the effect of creating oxygen with sunlight. The advantage of this concept is that no additional power electronics and electric cables and connections are needed. So far the major drawback is the stability of the used materials, which is only a few tens of hours [3,4]. Another disadvantage is that the system cannot be used to utilize the generated energy directly in the form of electricity. In literature different combination of solar cells with various electro-catalytic materials have been investigated [5–8]. In Ref. [9] Ronge et al. gives a thorough historic overview on conversion efficiencies from the 1970 up to 2015. In 2016 May et al. [3] showed a solar-to-hydrogen (STH) conversion efficiency of 16.8%[1] according to the higher heating value (HHV, all efficiency values in this work are be related to the HHV). Recently, Young et al. [10] exceeded this value with an STH conversion efficiency of 20.1%.[2]

In this work a hydrogen concentrator (HyCon) [11] which combines a III-V solar cell with a PEM electrolysis cell is used. In a HyCon cell the solar cell is not in direct contact with water but it is also not spatially separated from the electrolysis cell. A schematic view of the HyCon concept is depicted in Fig. 1. Sunlight is focused by a Fresnel lens onto a multi-junction solar cell. The solar cell is located directly on top of the anode of the electrolysis cell. The front side of the solar cell is connected with an electrical connection to the cathode side of the electrolysis cell. Beside this electrical connection similar advantages as for the PEC apply. There is no need for additional power electronics and for further electrical connections to connect solar cells and modules. Furthermore this concept is very stable due to the separation between the solar and the electrolysis cell by a suitable material as titanium. With this concept a maximum efficiency of 18.2% was reached in the past [12,13].

Various research groups have combined multi-junction solar cells with electrolysis cells [7,12–17]. Often these combinations include several interconnected solar cells that are combined with several PEM electrolysis cells. Another useful overview concerning double and triple-junction solar cells combined with electrolysis cells is given in Ref. [18]. Up to now Jia et al. reports the highest indoor-measured solar-to-hydrogen conversion efficiency of 39.1%[3] in a laboratory setup with a quadruple-junction solar cell [19]. For outdoor systems the highest efficiency of 29.1%[4] has been reached by Nakamura et al. [16]. They combined several concentrating PV (CPV) mono modules with several electrolysis cells. However, when efficiencies are compared, the type of solar cell has always to be taken into account, as the efficiency of the solar cell is mainly responsible for the total efficiency. For III-V multi-junction solar cells the efficiency varies from approximately 20% to a maximum of 46% [20], depending on the materials that are used, the number of implemented junctions and the concentration factor. Furthermore the efficiency is mostly measured in indoor setups where no additional optical losses occur. One major peculiarity of most publications in this field is that the electrolysis cells work close to the thermoneutral voltage and very low current densities of several mA. This enables high voltage efficiencies but often neglects the reduced Faraday efficiency or assumes it to be close to 100%. However, in PEM electrolysis cells this is only a valid assumption at high current densities above 1 A/cm^2 [21,22]. Therefore, it is important to consider not only the solar-to-hydrogen efficiency but also economic factors such as the current density of the electrolysis cell.

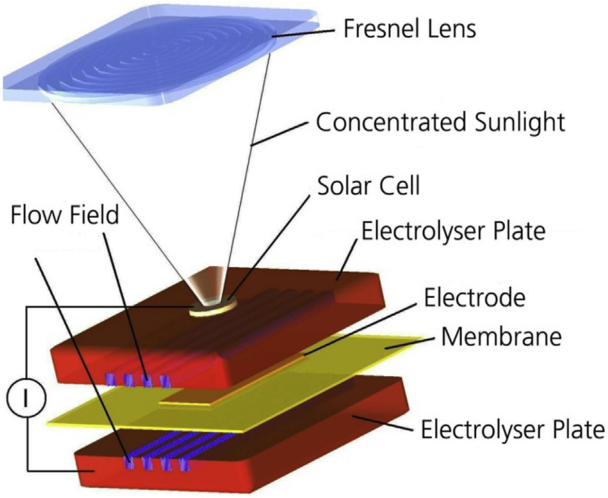

Fig. 1 – Schematic view of the HyCon concept [13]. A Fresnel lens focuses the sunlight on a multi-junction solar cell. This solar cell is directly connected to the anode of the electrolysis cell. The electric circuit is closed by an electrical wire connecting the cathode side to the front side of the solar cell.

In this work a HyCon demonstrator module is presented which was characterized on the roof of a building in Freiburg (Germany) in a long-term measurement. The design of the HyCon module was optimized to give a maximum performance and to understand the dependencies between water volume flow, temperature, voltage and current. A detailed thermal analysis of the HyCon system is intended to determine whether sufficient cooling of the electrolysis cells ($T_{max} = 90\ ^\circ C$) can be achieved via naturally convective water circulation and how effectively the waste heat from the solar cell is transported to the electrode. The experiments are also intended to clarify which temperatures are reached for the solar and the electrolysis cell in a HyCon system under practical operation conditions. These results can be used to further optimize the thermal coupling. Although certain authors claim that the combination of CPV and PEM electrolysis can achieve low investment costs [23,24], the HyCon demonstrator design is not cost-optimized at this stage.

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[1] value recalculated by multiplying with the ratio of the thermoneutral voltage and the reversible voltage in this case 1.48/1.23.

[2] value recalculated with thermoneutral voltage of 1.48 V.

[3] value recalculated with thermoneutral voltage of 1.48 V.

[4] value recalculated with thermoneutral voltage of 1.48 V.

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