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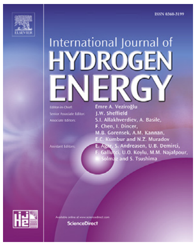

Performance assessment of concentrated solar power plants based on carbon and hydrogen fuel cells

Elena Díaz [a,b], *Michael Epstein* [a], *Manuel Romero* [a], *José González-Aguilar* [a,*]

[a] *IMDEA Energy Institute, Avda. Ramón de La Sagra 3, 28935, Móstoles, Spain*
[b] *Department of Chemical and Energy Technology, ESCET, Rey Juan Carlos University, 28933 Móstoles, Spain*

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A B S T R A C T

In spite of the recent success on the implementation of Concentrating Solar Power (CSP), still this technology needs a substantial enhancement to achieve competitiveness. This paper provides thorough insight after previous analyses on an alternative concept for higher efficiency CSP systems based on the replacement of the power block by an electrochemical conversion system. Concentrating solar energy is herewith used to decompose methane into hydrogen and carbon, which are used in hydrogen and carbon fuel cells for electricity generation. This approach envisages modular, efficient and flexible generation plants. Dispatchability can be achieved by storing the solid carbon. Solar-to-electricity efficiency was calculated assuming thermodynamic equilibrium composition and experimental data available from literature, and compared with those of conventional power generation systems and commercial CSP plants. It is concluded that this new-generation CSP concept is potentially able to produce power more efficiently than the current state-of-the art solar thermal power plants.

Introduction

Solar thermal electricity (STE) cost is currently not competitive with generation technologies based on fuels combustion or other renewables like photovoltaics or wind. Conventional strategy to accelerate cost reduction mainly lies in increasing concentrating solar power (CSP) performance through new developments on key components (such as heliostats, receivers), heat transfer fluids and thermal storage media, and innovative thermodynamic cycles [1–3]. A long-term research approach focuses on the replacement of turbomachinery in the power block by an electrochemical system. This alternative leads to shorter response times, almost-constant part-load efficiency and better grid integration. All of them are features that potentially allow increasing solar-to-electricity efficiency. Additionally water consumption is notably reduced compared to water/steam thermodynamic cycles.

Abbreviations: AFC, Alkaline fuel cell; CSP, Concentrated solar power; DCFC, Direct carbon fuel cell; FC, Fuel cell; HFC, Hydrogen fuel cell; MCFC, Molten carbonates fuel cell; PAFC, Phosphoric acid fuel cell; PEMFC, Proton exchange membrane fuel cell; PSA, Pressure swing adsorption; SOFC, Solid oxide fuel cell; SOFCIR, Solid oxide fuel cell with internal reforming; MSR, Methane steam reforming.

* *Corresponding author.*
E-mail address: jose.gonzalez@imdea.org (J. González-Aguilar).

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Nomenclature

C_s	Concentration ratio (suns)
$f.u.$	Fuel utilization (%)
ΔH_{FC}	Change in enthalpy in the fuel cell (kW)
I	Normal irradiance (kW/m^2)
LHV_{CH_4}	Methane low heating value (kJ/g)
$\dot{m}_{CH_4}$	Methane mass flow rate (g/s)
P_{FC}	Power obtained in the fuel cell (kW)
P_{losses}	Power consumed by process losses (kW)
Q_{FC}	Heat produced in the fuel cells (kW)
Q_{CH_4}	Power supplied by the methane feedstock (kW)
$Q_{preheating}$	Heat needed for methane preheating (kW)
$Q_{reactor}$	Solar power absorbed by the reactor/receiver (kW)
Q_{solar}	Concentrated solar power when preheating is not implemented (kW)
Q'_{solar}	Concentrated solar power when preheating is implemented (kW)
T_{FC}	Fuel cell operation temperature (ºC)
T_R	Reactor/receiver operation temperature (ºC)
X_i	Compound i conversion
Greek letters	
η_{abs}	Reactor/receiver absorption efficiency (%)
η_{CH_4}	Global process efficiency in terms of consumed feedstock (%)
$\eta_{CH_4-solar}$	Global process efficiency in terms of total energy consumed (%)
η_{FC}	Fuel cell efficiency (%)
σ	Stefan Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m^2K^4)

Within this general concept, it has been proposed using concentrated solar energy for methane cracking into hydrogen and solid carbon, which subsequently feed a hydrogen and a direct carbon fuel cell (HFC and DCFC) [4–6]. The intrinsic features of fuel cells (FCs) mentioned above and the capability of energy dispatch by means of carbon storage allow for covering properly instantaneous hydrogen/heat/electricity demand. Additionally energy conversion of methane-containing feedstocks are able to be used, including renewable ones such as landfill gas and biogas, after methane separation [7,8]. Finally the DCFC delivers lower and purer CO_2 emissions than conventional thermal power systems based on combustion of natural gas. Potentially this new approach allows for more efficient and modular generation plants.

Thermal or thermo-catalytic methane decomposition is an alternative to existing H_2 production processes from CH_4, like methane steam reforming (MSR). Although they seem analogous, usual MSR does not fully exploit the overall carbon content because methane is partially oxidized. Emissions are 3–5 times higher, and the required energy is higher by up to 1.7 times [9]. It has been claimed that MSR has higher environmental impact [10]. Thermodynamics shows that CH_4 decomposition starts at 300 °C, but temperatures in excess of 1200 °C are required to obtain a reasonable decomposition rate and yield due to the strong C–H bonds and the lack of polarity [11]. Reaction trace-products include acetylene (C_2H_2), ethylene (C_2H_4), butylene (C_4H_8), propylene (C_3H_6) and ethane (C_2H_6) [5]. Both, temperatures and by-products, can be significantly reduced using a catalyst, which can be carbonaceous [12], metallic [13], metal oxide based [14] or silica based [15]. Different kinds of solid carbon (carbon black, nanotubes, nanofibers, flakes, films) can be produced depending on the operation conditions, the type of reactor and the catalyst. It is possible to use solar energy for the decomposition [16]; however methane cannot be directly heated by solar irradiation because hydrocarbons poorly absorb in the solar spectrum. For that reason, solar reactors are usually based on opaque walls that absorb the solar radiation and heat up the gas (indirect heating) or a transparent window that permit direct heating of particulate material dispersed in the CH_4 gas that absorbs the radiation (direct heating) [17]. This concept has been widely studied mainly by the research groups of Steinfeld at ETH-Zurich in Switzerland [18], Abanades, Rodat and Flamant at CNRS-PROMES in France [19] and Kogan, Yeheskel and Epstein of Weizmann Institute of Science in Israel [20]. In the University of Colorado, USA, by Dahl [21] and by Pinilla in CSIC, Spain, experiments have been performed as well [22].

Additionally, FCs are gaining more attention because it is based on a clean process with high efficiency and cost-effective potential [23]. Use of fuel cells in stationary applications has been technically proven in a wide range of scales [24,25], although their commercialization has been hastening in the last few years based primarily on their cost [26]. Canada, Japan, South Korea, and Europe are currently developing large-scale fuel cell systems, being South Korea the country where the larger FC power plants can be found, i.e. West Incheon Power Plant (16 MWe), Noeul Green Energy Co., in Seoul (20 MW), Busan Green Energy project (30.8 MW), Gyeonggy Green Energy Park in Hwasung (59 MWe) and Pyeongteak City power plant (460 MWe) [24,25]. A variety of FCs types exists depending on the fuel and the electrolyte material, each of them with different operation temperature (T_{FC}) and efficiency (η_{FC}). This efficiency is defined in Eq. (1) as the electric energy produced relative to the total chemical energy change [27]:

$$\eta_{FC} = \frac{P_{FC}}{\Delta H_{FC}}, \tag{1}$$

with P_{FC}, the power obtained, and ΔH_{FC}, the enthalpy change during the reaction.

Table 1 and 2 summarize different characteristics of hydrogen and carbon FCs. An important issue regarding DCFC performance is the impurities and ash content in the carbon, which is hindering the use of biochar. However, the carbon produced by solar thermochemical decomposition of methane is pure and advantageous for use in DCFCs [5].

A FC-based power system needs the fuel and oxidant supply apart from the electrolyte management, cooling and thermal management or reaction products removal [29]. Integration of fuel cells and methane decomposition reactors in different layouts has been reported. Thus Muradov et al. consider the simplest scheme in which a hydrocarbon decomposition reactor is combined to a direct carbon and a hydrogen fuel cells [8]. In spite of the simplicity of the layout,

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