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Assessment of a new integrated solar energy system for hydrogen production

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Abstract

In this paper, a novel integrated system that combines photocatalysis, photovoltaics, thermal engine and chemical energy storage for better solar energy harvesting is assessed using energy and exergy methods. The system generates hydrogen and sulfur from sulfurous waters specific to chemical and petrochemical industries. The solar light is split into three spectra using optical surfaces covered with selected dielectric coatings: (i) the high energy spectrum, consisting of photons with wavelengths shorter than ~500 nm, is used to generate hydrogen from water photolysis, (ii) the middle spectrum with wavelengths between ~500 nm and ~800 nm is used to generate electricity with photovoltaic (PV) arrays and (iii) the long wave spectrum of low energy photons with wavelengths longer than ~800 nm is used to generate electricity with a thermally driven Rankine engine (RE). The electricity generated by PV and RE is employed to generate additional hydrogen by electrolysis and to drive auxiliary devices within the system. A model is developed based on conservation equations and transport equations applied for each essential component of the system. The model allows for assessment of system performance and the comparison with other solar hydrogen production systems. A case study for an oil sands exploitation area where sulfurous aqueous wastes and hydrogen demand exist – Calgary (Alberta) – is presented. A solar tower configuration is selected as the best choice for a large scale system with 500 MW light harvesting heliostat field. Hourly predictions of system output are obtained. The devised system requires 5526 acres of land for the solar field and produces 41.4 t hydrogen per day. If a conventional solar tower would be used instead which generates power and is coupled to a water electrolysis system the hydrogen production is lower, namely 28.7 t/day. An economic scenario is considered by assuming that the co-produced sulfur and hydrogen are both valorized on the market for 25 years with a levelized price of 1.65 $/kg out of which 10% represents operation and maintenance costs. It is shown that the system is feasible provided that the required equity investment of capital is inferior to M$ 500.

Keywords: Solar energy; Hydrogen production; System integration; Photocatalysis; Rankine cycle; Exergy analysis.

1. Introduction

Hydrogen production by solar energy has extensively been studied during recent years. Some potential methods, such as photo-catalytic and photo-electrochemical water splitting, as discussed in Zamfirescu et al., 2011, have received increasing attention. It is important to note that the performance of photoelectrochemical systems are essentially influenced by several parameters, for example, the band gap energy of catalysts and the spectrum of solar radiation, factors that must be considered in the selection of photocatalysts and photoreactions (Getoff, 1990). Solid-state chemistry plays a major role in the development

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Nomenclature

A	area, m^2
c	speed of light constant, m/s
c_λ	photon constant, m/s
e	electron charge, C
$\dot{E}$	energy rate, W
$\dot{E}x$	energy rate, W
F	factor
FF	filling factor
h	Planck's constant
J	current density, A/m^2
$\mathcal{k}$	extinction coefficient
k	Botltzman constant
$\mathcal{n}$	refraction index
N	number of elements
$\dot{N}$	photon rate, s^{-1}
N_A	Avogadro's number
P	pressure, kPa
R	reflectance
$\mathcal{S}$	entropy, J/K
$\dot{\mathcal{S}}$	entropy rate, W/K
V	voltage, V
t	time, h
T	temperature, K

Greek letters

η	energy efficiency
ψ	exergy efficiency

Subscript

abs	absorbed
bkw	backward
cat	catalysis
dni	direct normal spectral irradiation
fwd	forward
h	heliostats
λ	wave length
loss	energy losses
oc	open circuit
oper	operation
PC	photocatalysis
ph	photon
PV	photovoltaic
refl	reflective surface
sc	short circuit
TH	thermal
year	year

of potential photoelectrochemical systems for hydrogen production (Nowotny et al., 2007).

According to Kromer et al. (2011), the US Department of Energy (DoE) selected solar tower technology combined with thermochemical water splitting as the most promising one. The DoE established the hydrogen production goal with concentrated solar radiation to $6/kg for 2015 and $2–3/kg for 2025. In a review of solar tower system Romero et al. (2002) show that this technology is on the verge of commercialization as is proven feasible for sites with annual insolation of around 2 MW h/m^2 yr. At least 14 remarkable prototype plants covering a range of thermal power from 2 to 30 MW were successfully demonstrated in the last 30 years. A system lifetime of 45 years, comparable to nuclear and conventional fossil fuel power plants, is achievable (Vogel and Kalb, 2010).

The major cost item of concentrated solar tower systems is represented by heliostat field which, according to Vogel and Kalb (2010), takes approx. 40% of the investment. With a simple calculation one can estimate roughly the required cost margin for square meter of heliostat required to achieve the goal of DOE of $2/kg of hydrogen. Thus, with 2 MW h/m^2.yr incident radiation one calculates the total solar energy per square meter of heliostat for the entire system lifetime to 324 GJ/m^2. In terms of HHV, this energy is equivalent to that of 2285 kg of hydrogen, which is further equivalent to a total worth of $4570 per square meter.

With an interest rate of 4% (which is common for large scale projects of hundreds of MW range, see Vogel and Kalb, 2010) the present worth – corresponding to investment for 45 year timespan – is $4570/1.04^{45} = \$782$. Whence the heliostat cost must be significantly much cheaper than $(40\%) \times 782 = \$312$ per m^2 for the ideal case (all incident energy converted to hydrogen). The DoE's projected solar-to-hydrogen conversion efficiency is according to Kromer et al. (2011) in the range of 30–40% for 2025. Consequently the cost of the heliostat must be reduced below $90/$m^2$ for the DoE's goal to be achieved.

It is arguably justified in Vogel and Kalb (2010) that such low costs can be obtained by mass production of heliostat units. A parallel strategy to speed-up the large scale solar hydrogen technology commercialization is by finding alternative routes of improving the efficiency while keeping similar investment cost. An increase of hydrogen generation efficiency to 45% will allow for heliostat cost of $120/$m^2$, a more realistic figure. Kromer et al. (2011) evaluated the most relevant thermochemical cycles for hydrogen production with concentrated solar radiation and show that only the thin-film ferrite cycle is projected to achieve the desired efficiency under cost constraints by ensuring the long term cost goal of hydrogen below $3/kg.

According to Dincer and Zamfirescu (2012) it appears that the decisive factor for success of large-scale solar hydrogen production is the synergistic integration of key technologies and multiple valuable products generation