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Photovoltaic solar energy conversion for hydrogen production by alkaline water electrolysis: Conceptual design and analysis

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ABSTRACT

The use of solar energy for electricity generation and use of this electricity for hydrogen production by alkaline water electrolysis promises to be a truly sustainable scheme for the postulated hydrogen economy. This work addresses the design of a standalone solar photovoltaic (PV) energy system that meets the energy requirements of the electrolysis process, followed by the performance analysis under different environmental conditions. Energy requirement for electrolysis depends on the hydrogen production rate desired and the operating conditions of the electrolysis cell and it has been predicted from an essentially thermodynamic analysis. Mean solar irradiation data is estimated from location specific meteorological data. The current-voltage output characteristics of the solar modules have been predicted as function of the solar irradiation using the five parameter, single diode model of a solar panel and they have been linked to the production rates of hydrogen. The module behaviour and its thermodynamic and conversion efficiencies have also been predicted for actual operating conditions. Thus a step-by-step simplified approach for the preliminary PV power system design and analysis for an electrolysis based hydrogen production unit has been presented in this study.

1. Introduction

The use of hydrogen as an important energy carrier for the future has been widely proposed [1]. The hydrogen based energy system is not only an alternative to carbon based fossil fuels on which we are primarily dependent for our energy requirements today, it is also expected to become a necessity in the face of depleting fossil fuel reserves and increasing concerns about environmental pollution arising from green house gas emission when using the conventional fossil fuels. Apart from its use in the energy sector, hydrogen has wide spread applications as a raw material in the chemical, petroleum and nuclear industries and most of the demand is currently met by production of hydrogen from hydrocarbon resources [2]. Hydrogen production from an abundantly available raw material like water and use of renewable energy resources like solar energy for hydrogen production by alkaline water electrolysis are truly representative of a possible environmental friendly and sustainable solution (albeit an initially expensive one even with the technology currently available) that will at least partly meet the increasing global demands for energy and ensure long term energy security [3].

Alkaline water electrolysis can be carried out in stacks of electrolysis cells by using an electrolyte solution of around 30% potassium hydroxide in water. The current to be supplied depends on the production rate of hydrogen desired. The produced hydrogen and oxygen gases are kept separated in the cell through the use of a gas-impermeable but ion-conducting membrane like asbestos or Zirfon™ and they are subsequently separated from the electrolyte in bubble column-type gas separators fitted with wire mesh demister pads. Thus very high purity hydrogen as well as valuable by-product oxygen (having applications in manufacturing processes, chemical process industries, oxidative waste treatment processes and medical requirements) can be simultaneously produced and recovered in such a system [4,5].

The only hindrance to large scale electrolytic hydrogen production is the prohibitive cost of electrical power. Roof top mounted or ground located solar photovoltaic (PV) modules at the site of hydrogen production can be used to generate the electricity required for the process, thus allowing clean and power-grid independent operation and ultimately enormous reduction in process operating costs, as solar energy is available free of cost and only an initial investment in the solar PV modules, batteries and

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Nomenclature

a	lumped ideality factor for the PV module under any condition (dimensionless)
a_r	lumped ideality factor for the PV module under reference condition (dimensionless)
a_{roof}	solar irradiance absorptivity coefficient of the roof (m^2 - W^{-1} K^{-1})
A	area of the module exposed to solar radiation (m^2)
Cp_{air}	specific heat capacity of air (J kg^{-1} K^{-1})
E_g	solar PV material band gap energy (eV)
$E_{g.ref}$	band gap energy for silicon (1.121 eV)
$E_{T,P}$	reversible cell potential for water electrolysis at T and P (V)
Ex_{elec}	electrical exergy rate (W)
Ex_{in}	solar input exergy rate (W)
Ex_{out}	output exergy rate (W)
Ex_t	thermal exergy destruction rate (W)
F	Faraday's constant (96,485 C mol^{-1})
F_{br}	radiation view factor for back of module and roof (dimensionless)
F_{bs}	radiation view factor for back of module and sky (dimensionless)
F_{fr}	radiation view factor for front of module and roof (dimensionless)
F_{fs}	radiation view factor for front of module and sky (dimensionless)
g	acceleration due to gravity (9.81 m s^{-2})
H	length of the PV module (m)
h_b	convective heat transfer coefficient for back surface of module (W m^{-2} K^{-1})
h_c	combined free and forced convection heat transfer coefficient (W m^{-2} K^{-1})
h_f	combined convective heat transfer coefficient for front surface of module (W m^{-2} K^{-1})
h_{fr}	forced convection heat transfer coefficient (W m^{-2} K^{-1})
h_n	free convection heat transfer coefficient (W m^{-2} K^{-1})
I	module output current under any operating condition (A)
I_b	beam or direct radiation received by a surface (W m^{-2})
I_d	diffuse radiation received by a surface (W m^{-2})
I_g	global irradiance on a horizontal surface (W m^{-2})
I_L	photo current in the PV module at any condition (A)
I_{Lr}	photo current in the PV module at reference condition (A)
I_{mp}	module current at maximum power point (A)
I_N	direct beam irradiance on a surface perpendicular to the direct beam (W m^{-2})
I_{ON}	extraterrestrial radiation measured on a plane normal to the radiation (W m^{-2})
I_O	saturation current in the PV module under reverse bias at any condition (A)
I_{Or}	saturation current in the PV module under reverse bias at reference condition (A)
I_S	extra-terrestrial solar constant (1367 W m^{-2})
I_{sc}	module short circuit current (A)
I_t	total radiation received by a surface (W m^{-2})
$I_{t,ref}$	total radiation received by a surface under reference conditions (W m^{-2})
L	characteristic dimension for the solar module (m)
k	Boltzmann constant ($1.38 * 10^{-23}$ J K^{-1})
k_{air}	thermal conductivity of air (W m^{-1} K^{-1})
K_1, K_2	lumped atmospheric parameters for diffuse radiation (dimensionless, W m^{-2})
m	air mass (dimensionless)
n	day number in a year (dimensionless)
n_e	number of electrons transferred during electrolysis (dimensionless)
n_i	ideality factor (dimensionless)
$NOCT$	nominal operating cell temperature (C)
Nu_L	free convection Nusselt number for heat transfer from a flat, inclined plate (W m^{-2} K^{-1})
P	electrolysis pressure (Pa)
P_{max}	maximum power output from solar module (W)
Pr	Prandtl number (dimensionless)
q	electronic charge ($1.602 * 10^{-19}$ C)
Q_{in}	thermal energy input to the PV module (W)
Q_{loss}	thermal energy loss from the PV module (W)
Q_{power}	electrical power output from the PV module (W)
Ra_L	Rayleigh number for free convection (dimensionless)
R_b	conversion factor for beam radiation (dimensionless)
R_d	conversion factor for diffuse radiation (dimensionless)
Re	Reynolds number (dimensionless)
R_r	conversion factor for reflected radiation (dimensionless)
R_s	series resistance at any condition (Ω)
R_{sh}	Shunt resistance at any condition (Ω)
R_{shr}	shunt resistance at reference condition (Ω)
R_{sr}	series resistance at reference condition (Ω)
ST	solar time (h)
T	electrolysis temperature (K)
T_m	module temperature during operation (K)
T_{ref}	reference temperature of module (K)
T_{roof}	temperature of the roof (K)
T_R	Linke turbidity factor (dimensionless)
T_s	sun temperature (5780 K)
T_{sky}	temperature of the sky (K)
T_∞	ambient temperature at the site (K)
v_{wind}	wind velocity (m s^{-1})
V	module output voltage under any operating condition (V)
V_{mp}	module voltage at maximum power (V)
V_{oc}	module voltage at open circuit (A)
W	width of the PV module (m)

Greek symbols

α	lumped atmospheric parameter for beam radiation at any location (dimensionless)
α_{air}	thermal diffusivity of air (m^2 s^{-1})
α_T	temperature coefficient of current of the solar module (A $°C^{-1}$)
β	angle of tilt of the solar PV panels (degree)
β_{air}	coefficient of volumetric expansion of air (K^{-1})
β_T	temperature coefficient of voltage of the solar module (V $°C^{-1}$)
δ	solar declination angle (degree)
$\Delta G_{T,P}$	free energy change in water electrolysis process (J mol^{-1} hydrogen)
$\in$	integrated Rayleigh scattering optical thickness of the atmosphere (dimensionless)
ε_b	emissivity of the back surface of the PV module (dimensionless)
ε_f	emissivity of the front surface of the PV module (dimensionless)
γ	solar azimuth angle (degree)
η	conversion efficiency (dimensionless)
μ_{air}	viscosity of air (Pa s)
ν_{air}	kinematic viscosity of air (m^2 s^{-1})
ρ	ground reflection coefficient (dimensionless)
ρ_{air}	density of air (kg m^{-3})
σ	Stefan-Boltzmann constant (W m^{-2} K^{-4})
θ_i	angle of incidence of the sunrays (degree)
θ_z	solar zenith angle (degree)
φ	longitude of the site (degree)
ψ	exergetic efficiency (dimensionless)
Ω	hour angle (degree)