ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–12

Available online at www.sciencedirect.com

ScienceDirect

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

A new sustainable hydrogen clean energy paradigm

Alvin G. Stern *

AG STERN, LLC, Newton, MA, 02467, USA

ARTICLE INFO

Article history:
Received 25 September 2017
Received in revised form
19 December 2017
Accepted 27 December 2017
Available online xxx

Keywords:
Hydrogen fuel cell electric generator
Safe hydrogen generation
Hydrogen on demand
Zero emissions
Hydrogen clean energy cycle
Novel hydrogen energy paradigm

ABSTRACT

We analyze the feasibility of a novel, hydrogen fuel cell electric generator to provide power with zero noise and emissions for myriad ground based applications. The hydrogen fuel cell electric generator utilizes a novel, scalable apparatus that safely generates hydrogen (H_2) on demand according to a novel method, using a controlled chemical reaction between water (H_2O) and sodium (Na) metal that yields hydrogen gas of sufficient purity for direct use in fuel cells without risk of contaminating sensitive catalysts. The sodium hydroxide (NaOH) byproduct of the hydrogen producing reaction, is collected within the apparatus for later reprocessing by electrolysis, to recover the Na reactant. The detailed analysis shows that the novel, hydrogen fuel cell electric generator will be capable of meeting the clean power requirements for residential and commercial buildings including single family homes and light commercial establishments under a wide range of geographic and climatic conditions.

Introduction

There is a need in the modern world to provide sustainable means of producing clean energy economically, on a monumental scale. The world's population is inexorably increasing toward the 10 billion mark and carbon based fossil fuel consumption has increased accordingly, leading to unacceptable levels of air pollution in the major conurbations of both advanced and developing countries [1–4]. Although much of the pollution arises from burning carbon based fossil fuels inside internal combustion engines (ICEs) of motor vehicles and ships, a significant contribution is also made by coal burning thermal power plants used for electricity generation [5,6].

Hydrogen (H_2) which is stored in near limitless quantity in sea water is the only alternative fuel that is more abundant and environmentally cleaner with the potential of having a lower cost than nonrenewable carbon based fossil fuels, assuming that engineering challenges related to safe implementation and economical extraction of the hydrogen are overcome. Research on hydrogen storage and generator systems based on water (H_2O) remains active.

Extensive work has been reported in the scientific literature using sodium borohydride ($NaBH_4$) dissolved in water (H_2O) to form an aqueous solution, as a means of storing hydrogen, with its subsequent catalytic decomposition via hydrolysis to generate hydrogen (H_2) on demand and sodium borate ($NaBO_2$) byproduct [7–12]. The metal lithium (Li) and its hydrides, namely, lithium hydride (LiH) and lithium borohydride ($LiBH_4$) have been the focus of considerable research for their reactions with water (H_2O) for hydrogen generation [13–15]. The metal aluminum (Al) has also been studied for its

* Tel.: +1 617 669 6029; fax: +1 617 527 4331.
E-mail address: inquiries@agstern.com.

https://doi.org/10.1016/j.ijhydene.2017.12.180

Please cite this article in press as: Stern AG, A new sustainable hydrogen clean energy paradigm, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2017.12.180

Nomenclature

E_{BAT}	energy capacity of battery in a battery electric vehicle (BEV) [kWh]
E_{Na40}	total energy of hydrogen fuel cell electric generator, 40 cells – Na metal [kWh]
E_{Na160}	total energy of hydrogen fuel cell electric generator, 160 cells – Na metal [kWh]
E_{NaH40}	total energy of hydrogen fuel cell electric generator, 40 cells – NaH [kWh]
E_{NaH160}	total energy of hydrogen fuel cell electric generator, 160 cells – NaH [kWh]
E_T	mean monthly electric energy consumption [kWh/month]
ΔG	change in Gibbs free energy [kJ]
ΔH	change in enthalpy [kJ]
M	molar mass [g/mol]
P_{FC}	power output of fuel cell [kW]
P_{H_2}	pressure of hydrogen ($H_{2(g)}$) [kPa]
Q_C	heat of combustion [kJ]
Q_{Carnot}	Carnot heat [kJ]
Q_{lat}	latent heat [kJ]
R_{BEV}	range of battery electric vehicle (BEV) [miles]
S_P	practical salinity (PSS-78)
ΔS	change in entropy [J/K]
t_{RC}	time duration to recharge a battery [hours]
T	temperature [K] or [°C]
T_2	upper temperature of working fluid [K]
T_1	lower temperature of working fluid [K]
W_m	mechanical work [kJ]
W_e	electrical work [kJ]
W_{FC}	electrical work extracted from $H_{2(g)}$ by a fuel cell [Wh/kg]
η	efficiency [%]
η_{max}	maximum theoretical efficiency [%]
ρ	density [g/cm^3]
P_0	standard atmospheric pressure 101 325 [Pa]
T_{Eu}	eutectic temperature of NaCl–H_2O solution −21.2 [°C]
M_{NaH}	molar mass, sodium hydride (NaH) 23.997 [g/mol]
ρ_{NaH}	density, sodium hydride (NaH) 1.16 [g/cm^3]

potential use as a reactant with water (H_2O) for hydrogen generation [16]. In previous work, we have shown that a novel hydrogen generation apparatus using a controlled chemical reaction between water (H_2O) and sodium (Na) metal can be made to function reliably under a wide range of ambient temperatures from −21.2 °C (251.95 K) to 56.7 °C (329.85 K) to safely generate high purity hydrogen ($H_{2(g)}$) fuel on demand for motor vehicles equipped with Otto or Diesel internal combustion engines (ICEs) while achieving an equal driving range as with conventional fuel [17]. We now expand beyond our previous work to present and analyze a new hydrogen clean energy paradigm wherein a hydrogen fuel cell electric generator comprising the novel, scalable, hydrogen generation apparatus, is shown capable of providing power for motor vehicles and for wide ranging applications in ground based clean power generation.

At the present time, large scale ground based electric power generation and distribution is centered on an electric grid and an evolving smart grid system [18,19]. The electric grid is meant to allow all art of electric power generation units including renewable systems, to supply power that is distributed via transmission lines and substations to households, commercial businesses and industry. The principal problem with the electric power generation and distribution system centered on the electric grid exists because the supply of electric power in the U.S.A. and around the world is inadequate to meet the large projected growth in demand from the proliferation of battery electric vehicles (BEVs) [20,21]. Secondly, the electric currents required for rapidly charging BEVs with 24–100 kWh batteries in 1 hour or less, can exceed 100 Amperes from single phase 240 VAC outlets for an individual vehicle, and there could be many adjacent BEVs electrically charging at one time. The sustained delivery of such high currents requires the installation of large transformers, as the existing ones are not capable of supplying the electrical loads. In addition to upgraded transformers for high current delivery, the local municipal medium voltage (15–35 kV) transmission lines would also have to be significantly upgraded to support the larger transformers servicing the BEV electrical loads. Thirdly, a BEV by its inherent design requires a dedicated charging station and in high density urban areas it is not feasible technically and economically to convert every parking space at a residential apartment block, office tower, or on the street into a BEV charging station. It is therefore evident that it is virtually impossible to support widespread BEV proliferation using ground based electric power generation and delivery methods centered on the existing electric grid, and attempting to do so could lead to instability and collapse, due to insufficient electric power generation capacity and inadequate electric grid infrastructure.

The novel, hydrogen fuel cell electric generator forms part of a sustainable, closed clean energy cycle in conjunction with self-contained solar powered electrolytic sodium (Na) metal production plants, and will be shown capable of overcoming all the limitations of existing electric grid based power generation and distribution systems, to deliver distributed renewable electric power with zero noise and emissions for wide ranging applications [17,22].

Hydrogen fuel cell electric generator characteristics

The hydrogen fuel cell electric generator design is based on a novel, scalable, hydrogen generation apparatus capable of safely and reliably producing high purity hydrogen ($H_{2(g)}$) fuel on demand according to the chemical reaction in Eq. (1) [17].

$$2Na_{(s)} + 2H_2O_{(l)} \rightarrow H_{2(g)} + 2NaOH_{(s)} \quad (1)$$

The sodium hydroxide (NaOH) byproduct from the $H_{2(g)}$ producing chemical reaction in Eq. (1) is recovered during refueling of the hydrogen generator for reprocessing in

Please cite this article in press as: Stern AG, A new sustainable hydrogen clean energy paradigm, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2017.12.180