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

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A new sustainable hydrogen clean energy paradigm

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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.

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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

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

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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

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self-contained solar powered electrolytic sodium (Na) metal production plants according to Eq. (2), to recover the Na metal for reuse in generating $H_{2(g)}$ fuel [22].

$$4Na^+ + 4OH^- \rightarrow 4Na_{(l)} + 2H_2O_{(g)} + O_{2(g)} \quad (2)$$

Implementation of a hydrogen fuel, sustainable, closed clean energy cycle based on Eqs. (1) and (2) using solar powered electrolysis to reprocess NaOH, enables elimination of carbon dioxide (CO_2) emissions. In contrast, the existing industrial method of generating hydrogen ($H_{2(g)}$) gas using steam reforming of natural gas, the latter containing mostly methane (CH_4), produces significant quantities of carbon dioxide (CO_2), a greenhouse gas [23].

The high purity hydrogen ($H_{2(g)}$) fuel produced by the novel hydrogen generation apparatus is derived from ordinary salinated (sea) or desalinated (fresh) water (H_2O) rather than from carbon based fossil fuels and therefore does not contain even trace amounts of carbon monoxide or sulfur compounds that can contaminate the sensitive platinum (Pt) catalysts present in proton exchange membrane (PEM) fuel cells or any other types of catalysts in fuel cells. Steam reforming of methane however, produces significant quantities of carbon monoxide (CO) even after application of the shift reaction meant to transform CO into carbon dioxide (CO_2). The presence of even minute quantities of CO on the parts per million (ppm) order of magnitude in $H_{2(g)}$ fuel, results in rapid poisoning of sensitive platinum (Pt) catalysts present in the latest generation of low operating temperature, proton exchange membrane (PEM) fuel cells [24]. Catalysts based on a mixture of platinum and ruthenium (Pt-Ru) developed to overcome the sensitivity of pure Pt to carbon monoxide poisoning are not cost effective for large scale application due to the dearth of ruthenium [25].

The use of seawater as a reactant in Eq. (1), concentrated to as much as 252.18 g of sea salt solute per kilogram of seawater solution provides a fusion temperature $T_{Eu} = -21.2\ ^\circ C$ (251.95 K), that is equivalent to the eutectic temperature of a 23.18% by weight NaCl in NaCl–H_2O solution [26,27]. The concentrated sea salt in seawater solution allows the hydrogen generator to operate reliably over a wide ambient temperature range from −21.2 °C (251.95 K) to 56.7 °C (329.85 K) prevailing in the 48 conterminous states of the U.S.A. [17] When the byproducts of the chemical reaction in Eq. (1) consisting primarily of NaOH and NaCl, the latter obtained from seawater, are recovered and recycled using solar powered electrolysis, more Na metal will have been produced by the electrolysis than was originally available when the hydrogen generation apparatus was freshly fueled. Therefore, it becomes possible to passively increase the amount of sodium (Na) metal in the closed hydrogen fuel clean energy cycle [17].

Table 1 provides the physical properties of the chemical reactants and products in Eq. (1).

The hydrogen generation apparatus has a wide range of potential applications in power generation as illustrated in Fig. 1, due to the versatile properties of the hydrogen ($H_{2(g)}$) fuel that enable direct chemical combustion as well as direct electrochemical oxidation of the $H_{2(g)}$.

In Fig. 1, the scalable, hydrogen generation apparatus is shown capable of providing $H_{2(g)}$ fuel for internal combustion engine (ICE) motor vehicles, fuel cell electric vehicles (FCEVs) with large, 10–75 kW class primary power fuel cells, as well as smaller 1–5 kW class secondary power fuel cells for onboard continuous recharging of battery electric vehicles (BEVs). The hydrogen fuel cell electric generator concept using the scalable hydrogen generation apparatus can be extended to a wide range of ground based applications, including providing renewable power with zero noise and emissions to single family homes and light commercial establishments.

The direct chemical combustion of $H_{2(g)}$ fuel inside internal combustion engines (ICE) occurs according to Eq. (3).

$$H_{2(g)} + \tfrac{1}{2}O_{2(g)} \rightarrow H_2O_{(g)} \quad (3)$$

The enthalpy of the direct chemical combustion reaction in Eq. (3) is given as $\Delta H = -241.84$ kJ/mol where $Q_C = -\Delta H$ corresponding to the *lower heating value* since the water (H_2O) product after combustion exists in a vapor state [37,38]. The *lower heating value* entails that direct chemical combustion of 1 mol of $H_{2(g)}$ fuel yields 241.84 kJ of energy, corresponding to 119.97 MJ/kg or 33,325 Wh/kg, the highest energy density per unit mass of any chemical fuel. The second law of thermodynamics governs the efficiency by which the thermal energy from combustion of the $H_{2(g)}$ fuel in Eq. (3), can be converted to mechanical work W_m, in a heat engine of the Otto or Diesel type. For an idealized heat engine that follows the Carnot cycle, the maximum theoretical efficiency is given in Eq. (4).

$$\eta_{max} = \frac{W_m}{Q_C} = \frac{T_2 - T_1}{T_1} \quad (4)$$

In Eq. (4), T_2 and T_1 represent the upper and lower temperatures in Kelvin of the working fluid, respectively. In practice, T_2 is the temperature reached by the working fluid when heat is added during fuel combustion and T_1 can correspond to the temperature of the ambient into which the working fluid expands. The Carnot heat that is lost is given as $Q_{Carnot} = (T_1/T_2) \times Q_C$. The Otto engines operate with an efficiency $\eta = 25–30\%$, while Diesel engines and modern thermal

Table 1 – Physical properties of chemical reactants and products in Eq. (1) at $T = 298.15$ K and $P_0 = 101\ 325$ Pa.

Element/Compound	Molar mass (M) [g/mol]	Density (ρ) [g/cm³]
Sodium (Na)	22.989 769 28(2) [28]	0.96601 (31.3 °C) [32]
[a]Pure (VSMOW) Water (H_2O)	18.015 268 [29–31]	0.999 974 95 (3.983 035 °C) [33]
Standard Seawater (SSW, $S_P = 35$)		1.0237 [34]
Hydrogen (H_2)	2.015 88 [28]	0.0823 kg/m³ [35]
Sodium Hydroxide (NaOH)	39.997 109 28 [28]	2.13 [36]

[a] Vienna Standard Mean Ocean Water (VSMOW) [29].

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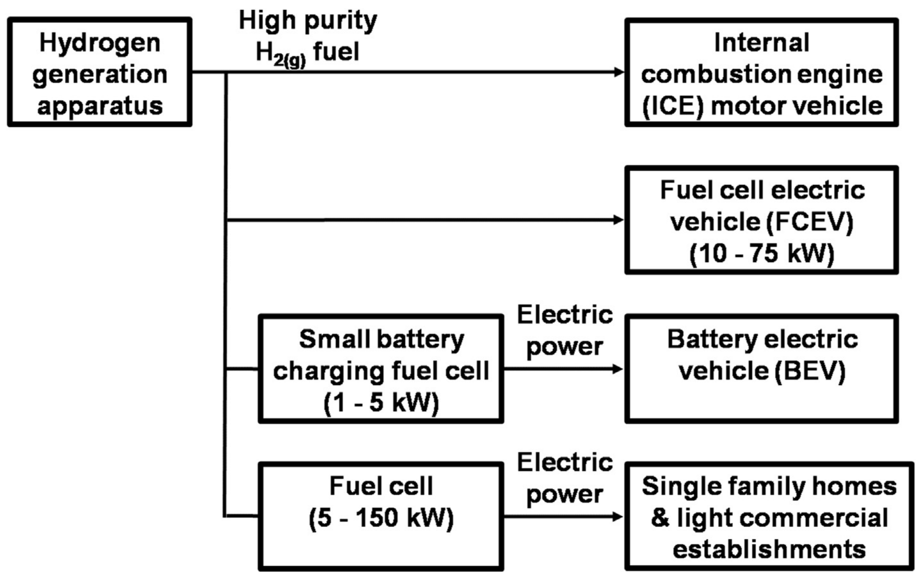

Fig. 1 – Applications in ground based clean power generation using the scalable, hydrogen generation apparatus.

power stations normally operate with an efficiency $\eta \approx 40\%$ [39].

When the $H_{2(g)}$ fuel is oxidized electrochemically, for example in a proton exchange membrane (PEM) fuel cell operating near room temperature ($T = 25–80\ ^{\circ}C$), the reaction that occurs is given in Eq. (5).

$$H_{2(g)} + \frac{1}{2}O_{2(g)} \rightarrow H_2O_{(l)} \quad (5)$$

The enthalpy of the direct chemical combustion reaction in Eq. (5) is given as $\Delta H = -285.85$ kJ/mol where $Q_C = -\Delta H$ corresponding to the *higher heating value* since the water (H_2O) is produced in liquid state. [37,38] The *higher heating value* entails that electrochemical oxidation of 1 mol of $H_{2(g)}$ fuel yields 285.85 kJ of energy, corresponding to 141.80 MJ/kg or 39,389 Wh/kg. The maximum electrical work W_e, that can be obtained from Eq. (5) is determined by the Gibbs free energy of the reaction $\Delta G = -237.19$ kJ/mol where $W_e = -\Delta G$. Thus, for electrochemical oxidation of the $H_{2(g)}$ fuel in a PEM fuel cell near room temperature, the maximum theoretical efficiency is given in Eq. (6).

$$\eta_{max} = \frac{W_e}{Q_C} \times 100 = 83\% \quad (6)$$

The latent heat that is lost during electrochemical oxidation of the $H_{2(g)}$ fuel is given as $Q_{lat} = -T\Delta S$ and corresponds to the Carnot heat Q_{Carnot}, lost in direct chemical combustion, where $Q_C = -\Delta H = W_e + Q_{lat}$. In the electrochemical oxidation of $H_{2(g)}$ fuel near room temperature ($T = 25–80\ ^{\circ}C$) not only is the enthalpy of the reaction in Eq. (5) greater due to the *higher heating value* compared to direct chemical combustion in Eq. (3) that yields the *lower heating value*, but also, the chemical energy of the $H_{2(g)}$ fuel is converted to electrical energy with a minimal latent heat Q_{lat}, while circumventing Carnot heat Q_{Carnot}, losses. In practice, various loss mechanisms contribute to lowering the efficiency of electrochemical oxidation of the $H_{2(g)}$ in a fuel cell from the theoretical limit given in Eq. (6) to $\eta = 60–70\%$. Therefore, the useful electrical work that can be extracted from the $H_{2(g)}$ by the fuel cell will be on the order of $W_{FC} = 0.6 \times 39{,}389$ Wh/kg $= 23{,}633$ Wh/kg. It is evident that the hydrogen fuel cell provides a significant efficiency enhancement for extracting useful work in the form of electrical energy W_e, from $H_{2(g)}$ fuel compared with ICEs that extract mechanical work W_m, from the $H_{2(g)}$ fuel with significantly lower efficiency. The hydrogen fuel cell operating near room temperature ($T = 25–80\ ^{\circ}C$) possesses ideal energy conversion attributes for use in a hydrogen fuel cell electric generator including high efficiency, low operating temperature as well as zero noise and emissions.

The hydrogen fuel cell electric generator comprises four principal functional units including a hydrogen generation apparatus that safely generates hydrogen fuel on demand at the time and point of use, a hydrogen fuel cell that can be an alkaline fuel cell (AFC) or proton exchange membrane (PEM) fuel cell or other type of fuel cell, a power conditioning stage that converts the DC voltage and current generated by the fuel cell into the DC or AC output voltage and current required by the application, and a control unit that ensures all functional units of the hydrogen fuel cell electric generator operate correctly to deliver the exact power required by the load efficiently, without wasting the $H_{2(g)}$ fuel. The functional diagram of the hydrogen fuel cell electric generator is shown in Fig. 2.

In Fig. 2, the hydrogen generation apparatus is designed to store generated $H_{2(g)}$ at a low pressure of 600 kPa (87 psi). [17] A pressure regulator controls the delivery pressure of $H_{2(g)}$ on the process side or output of the regulator that can be set to a relatively low 200 kPa (29 psi) value. To ensure optimal fuel use, a mass flow controller operated by the control unit can meter a precise flow of $H_{2(g)}$ to the fuel cell. The performance of the hydrogen fuel cell electric generator comprising the scalable hydrogen generation apparatus is summarized in Table 2.

In Table 2, the hydrogen fuel cell electric generator based on a 40 cell variant of the hydrogen generation apparatus provides a total energy $E_{Na40} = 124.9$ kWh. It is meant for portable applications by manufacturing using lightweight

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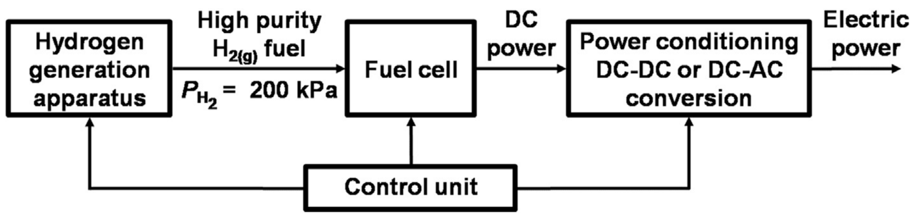

Fig. 2 – Functional diagram of the hydrogen fuel cell electric generator.

composite materials, for onboard continuous recharging of battery electric vehicles (BEVs) as indicated in Fig. 1. The larger 160 cell electric generator variant delivering E_{Na160} = 499.6 kWh of energy is intended for stationary applications where mass is of less concern and therefore, can be constructed from more traditional materials such as aluminum and stainless steel.

The chemical reaction in Eq. (1) implemented by the hydrogen generation apparatus to produce hydrogen ($H_{2(g)}$) fuel is exothermic and releases significant energy in the form of heat in addition to the energy contained in the $H_{2(g)}$ fuel listed in Table 2. The rate of heat energy release from Eq. (1) is determined by the power output level of the fuel cell in the hydrogen fuel cell electric generator. A low power fuel cell P_{FC} = 5 kW for example, requires less $H_{2(g)}$ fuel supplied per unit time, consequently resulting in a lower rate of heat energy release due to Eq. (1) within the hydrogen generation apparatus, compared to a higher power fuel cell. Assuming the hydrogen fuel cell electric generator comprises a proton exchange membrane (PEM) fuel cell that electrochemically oxidizes $H_{2(g)}$ according to Eq. (5) with an efficiency η = 60%, then it is possible to calculate the rate of heat energy released in the hydrogen generation apparatus as a function of the power of the PEM fuel cell as shown in Fig. 3.

In Fig. 3, it is clear that fuel cells with power ratings P_{FC} > 5 kW require larger flow rates of $H_{2(g)}$ resulting in higher levels of heat energy released per unit time in the hydrogen generation apparatus. The heat energy released by the exothermic chemical reaction between water (H_2O) and sodium (Na) metal in Eq. (1) can be harvested using a thermoelectric generator (TEG) to recharge a battery that powers the control unit of the hydrogen fuel cell electric generator shown in Fig. 2, or to heat the passenger cabin in a motor vehicle or the enclosed space inside a building.

Table 2 – Characteristics of the hydrogen fuel cell electric generators using Na metal to generate $H_{2(g)}$.

	40 cell generator [mol/kg]	160 cell generator [mol/kg]
Sodium (Na)	5244/120.558	20,976/482.232
[a]Pure (VSMOW) Water (H_2O)	5552/100.020	22,208/400.080
Hydrogen (H_2)	2622/5.285	10,488/21.14
Sodium Hydroxide (NaOH)	5244/209.744	20,976/838.976
	[kWh]	[kWh]
[b]Total energy	124.9	499.6

[a] Air free water as opposed to air-saturated water, the latter having a freezing point T = 273.1501 K [40].
[b] Total energy content assumes conversion of $H_{2(g)}$ in the fuel cell with an efficiency η = 60% of the *higher heating value*.

Hydrogen fuel cell electric generator based on sodium hydride

The same hydrogen fuel cell electric generator design based on a novel, scalable, hydrogen generation apparatus is also capable of safely and reliably producing high purity hydrogen ($H_{2(g)}$) fuel on demand according to the chemical reaction in Eq. (7) using sodium hydride (NaH) as a reactant instead of sodium (Na) metal. [17]

$$2NaH_{(s)} + 2H_2O_{(l)} \rightarrow 2H_{2(g)} + 2NaOH_{(s)} \quad (7)$$

The sodium hydride (NaH) reactant is more complicated to manufacture on a very large scale than sodium (Na) metal because it requires a separate plant for the coproduction of elemental H_2 in propinquity to the solar powered electrolytic sodium (Na) metal production plant. The elemental H_2 can be manufactured in an environmentally clean and sustainable way using solar powered electrolysis of water (H_2O) with photovoltaic (PV) panels, photocatalytic or photoelectrochemical (PEC) methods, or from biohydrogen generation using chemical, thermochemical, biological, biochemical, and biophotolytical methods [41]. For special applications, the NaH reactant can significantly enhance the performance of the hydrogen fuel cell electric generator by more than doubling the $H_{2(g)}$ generating capacity of the hydrogen generation apparatus using the same number of cells. The enhanced $H_{2(g)}$ generating capacity is achieved because NaH releases an extra mole of $H_{2(g)}$ fuel for every 2 mol of Na metal that react with water to produce 1 mol of $H_{2(g)}$ as becomes

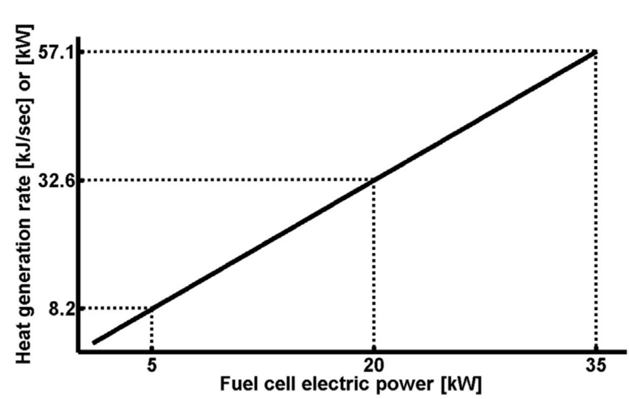

Fig. 3 – Heat generation rate in the $H_{2(g)}$ generator due to the chemical reaction between H_2O and Na metal.

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evident when comparing the chemical reactions in Eqs. (1) and (7). The molar mass of NaH is given as $M_{NaH} = 23.997$ g/mol that is similar to Na metal. Since NaH exists as a solid powder at room temperature and decomposes before melting at elevated temperatures, it is difficult to cast as a monolithic material. Its density as a compacted, solid powder can therefore range from a low value of $\rho_{NaH} = 0.92$ g/cm^3 to a high value of $\rho_{NaH} = 1.396$ g/cm^3 [37,42]. The performance of the hydrogen fuel cell electric generator comprising the scalable hydrogen generation apparatus using NaH reactant to generate $H_{2(g)}$ fuel according to Eq. (7), is summarized in Table 3.

In Table 3, the hydrogen fuel cell electric generator based on the 40 cell variant of the hydrogen generation apparatus using NaH reactant provides a total energy $E_{NaH40} = 287.4$ kWh for portable applications such as onboard continuous recharging of battery electric vehicles (BEVs), indicated in Fig. 1. The larger 160 cell electric generator variant using NaH reactant delivers $E_{NaH160} = 1149.6$ kWh and is intended for stationary applications.

The chemical reaction in Eq. (7) implemented by the hydrogen generation apparatus is less exothermic per mole of hydrogen ($H_{2(g)}$) fuel produced than Eq. (1), yet still releases significant energy in the form of heat in addition to the energy contained in the $H_{2(g)}$ fuel listed in Table 3. The rate of heat energy release from Eq. (7) is determined by the power output level of the fuel cell in the hydrogen fuel cell electric generator. Assuming the hydrogen fuel cell electric generator comprises a proton exchange membrane (PEM) fuel cell that electrochemically oxidizes $H_{2(g)}$ according to Eq. (5) with an efficiency $\eta = 60\%$, then it is possible to calculate the rate of heat energy released in the hydrogen generation apparatus as a function of the power of the PEM fuel cell as shown in Fig. 4.

The heat energy released by the exothermic chemical reaction between water (H_2O) and sodium hydride (NaH) calculated in Fig. 4, can be harvested using a thermoelectric generator (TEG) to recharge a battery that powers the control unit of the hydrogen fuel cell electric generator shown in Fig. 2 or to heat an enclosed space.

Table 3 – Characteristics of the hydrogen fuel cell electric generators using NaH to generate H_2.

	40 cell generator [mol/kg]	160 cell generator [mol/kg]
[a]Sodium hydride (NaH)	6032/144.750	24,128/579.0
[b]Pure (VSMOW) Water (H_2O)	6032/108.668	24,128/434.672
Hydrogen (H_2)	6032/12.160	24,128/48.64
Sodium Hydroxide (NaOH)	6032/241.263	24,128/965.052
	[kWh]	[kWh]
[c]Total energy	287.4	1149.6

[a] Density of NaH is considered as the arithmetic mean between the low and high density values with $\rho_{NaH} = 1.16$ g/cm^3 [37, 42].
[b] Air free water as opposed to air-saturated water, the latter having a freezing point T = 273.1501 K [40].
[c] Total energy content assumes conversion of $H_{2(g)}$ in the fuel cell with an efficiency $\eta = 60\%$ of the *higher heating value*.

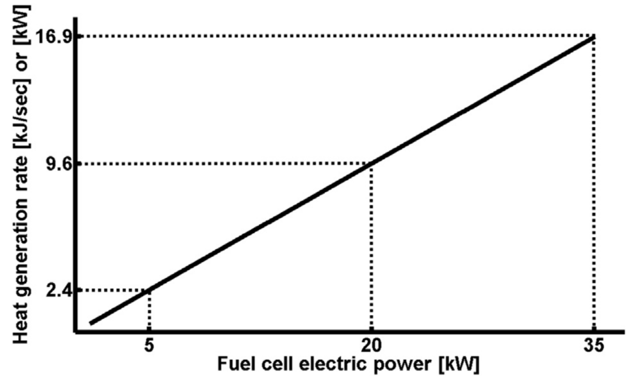

Fig. 4 – Heat generation rate in the $H_{2(g)}$ generator due to the chemical reaction between H_2O and NaH.

Method of application

The hydrogen fuel cell electric generator based on the 40 cell hydrogen generation apparatus described in Table 2, can be installed in a battery electric vehicle (BEV) to continuously recharge the electric battery and thereby extend the range of the motor vehicle. Considering as a test vehicle the 2013 Nissan Leaf BEV with a battery capacity $E_{BAT} = 24$ kWh and expected range $R_{BEV} = 73$ miles, the latter estimated from highly accurate probabilistic modeling by Needell et al., it is possible to calculate how the onboard hydrogen fuel cell electric generator can enhance the range of the vehicle [43]. Since the energy delivered by the 40 cell hydrogen generation apparatus using Na metal is given as $E_{Na40} = 124.9$ kWh, using it to recharge the 24 kWh battery of the BEV results in an enhanced range $R_{BEV} = (124.9 \text{ kWh}/24 \text{ kWh}) \times 73$ miles $= 379.9$ miles (611.4 km). A rated power of the fuel cell $P_{FC} = 5$ kW is sufficient to fully recharge the 24 kWh battery in a time duration given as $t_{RC} = 24 \text{ kWh}/5 \text{ kW} = 4.8$ hours. The range of the BEV thus becomes commensurate with the Otto or Diesel ICE equipped motor vehicles using liquid hydrocarbon fuels.

For special applications, fueling the 40 cell hydrogen generation apparatus with NaH reactant provides a delivered energy $E_{NaH40} = 287.4$ kWh, and using it to recharge the 24 kWh battery of the BEV results in an enhanced range $R_{BEV} = (287.4 \text{ kWh}/24 \text{ kWh}) \times 73$ miles $= 874.2$ miles (1406.9 km). Using a fuel cell with a rated power $P_{FC} = 5$ kW in the onboard hydrogen fuel cell electric generator can significantly reduce the cost of the motor vehicle compared with using a larger, 10–75 kW primary power fuel cell as the means to power the electric motor of the vehicle without an electric storage battery as indicated in Fig. 1. The hydrogen fuel cell electric generator can be installed on the roof of the motor vehicle in a resilient, lightweight enclosure capable of withstanding the effects of collisions and vehicle rollovers, as shown in Fig. 5.

The hydrogen fuel cell electric generator shown in Fig. 5 functions to recharge the battery of the BEV and thus, only electrical transmission lines traverse between the roof enclosure and the vehicle. In the event of an accident resulting in the roof mounted enclosure containing the hydrogen fuel cell electric generator becoming detached from the BEV, the

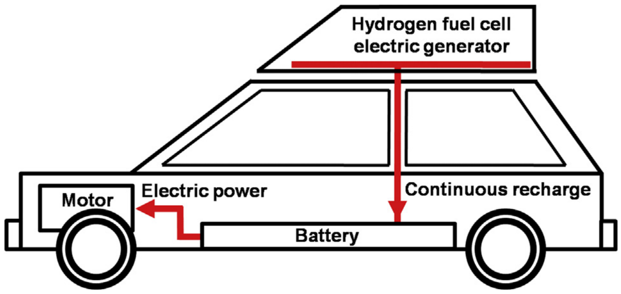

Fig. 5 – Hydrogen fuel cell electric generator installed on the roof to continuously charge the battery of a BEV.

passengers inside will be safe from any potential hydrogen leaks because the entire hydrogen generation system is contained within the roof mounted enclosure.

The larger hydrogen fuel cell electric generator based on the 160 cell hydrogen generation apparatus can be mounted on a concrete pad in a secure enclosure similar to pad mounted electric transformers, to provide autonomous electric power to single family homes and light commercial establishments. The hydrogen fuel cell electric generator enclosures can be surrounded by bollards and a chain link fence to thwart accidental ramming by motor vehicles or unauthorized entry. The Fig. 6 shows a hydrogen fuel cell electric generator installed in proximity to a single family home while Fig. 7 shows the hydrogen fuel cell electric generator installed near a commercial establishment such as a bank, pharmacy, restaurant, grocery or other store to provide renewable electric power with zero noise and emissions.

In Fig. 6, the hydrogen fuel cell electric generator based on the 160 cell hydrogen generation system operates autonomously to provide for the total energy needs of a single family home including electric power for kitchen and laundry appliances, lighting and electronics and electric heat pumps for heating and cooling. In Fig. 7, the hydrogen fuel cell electric generator based on the 160 cell hydrogen generation system provides for the total energy needs of light commercial establishments such as banks, pharmacies, restaurants, grocery

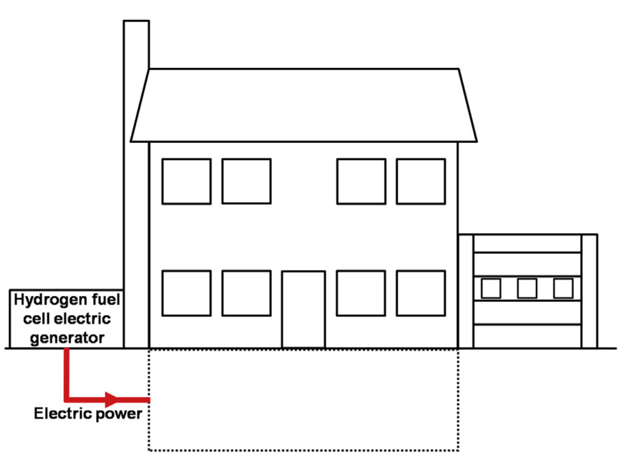

Fig. 6 – Hydrogen fuel cell electric generator with 160 cell hydrogen generation system installed on a concrete pad near a single family home.

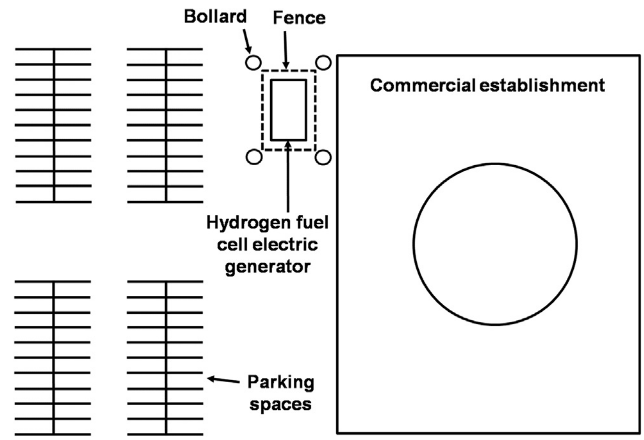

Fig. 7 – Hydrogen fuel cell electric generator with 160 cell hydrogen generation system installed on a concrete pad near a commercial establishment (Aerial View).

and other stores. The electric power supplied by the hydrogen fuel cell electric generator in the U.S.A. will be 120/240 VAC, 3-wire single phase service to a single family home and for a light commercial establishment it will be 120/208Y VAC, 4-wire three phase service as shown in Fig. 8.

In Fig. 8, the ground wire is electrically connected to the neutral wire for the single phase circuit as well as the three phase circuit. The 120/208Y VAC, 4-wire three phase power service represents the lowest standard three phase voltage that is meant for supplying light commercial establishments. Higher voltages such 277/480Y VAC, 332/575Y VAC or 347/600Y VAC, 4-wire three phase service can be supplied for more demanding commercial or industrial applications.

Performance of hydrogen fuel cell electric generator

It is shown through careful calculation and analysis means that the hydrogen fuel cell electric generator with performance characteristics summarized in Tables 2 and 3, will be capable of providing for the comprehensive energy needs of single family homes and light commercial establishments, the latter that can include banks, pharmacies, restaurants, grocery or other stores, with zero noise and emissions, under a wide range of geographic and climatic conditions. They will also provide power to battery electric vehicles (BEVs) for continuous onboard battery charging shown in Fig. 5, and for stationary charging when parked in the driveway of a single family home shown in Fig. 6, as well as when parked in the lot of a commercial establishment shown in Fig. 7.

Electric energy consumption of a single family home

The energy consumption of a small to medium size single family home located within the conterminous 48 states of the U.S.A., supplied by the hydrogen fuel cell electric generator based on the 160 cell hydrogen generation system can be estimated considering that all the kitchen and laundry appliances, household lighting and electronics, heat pump heating

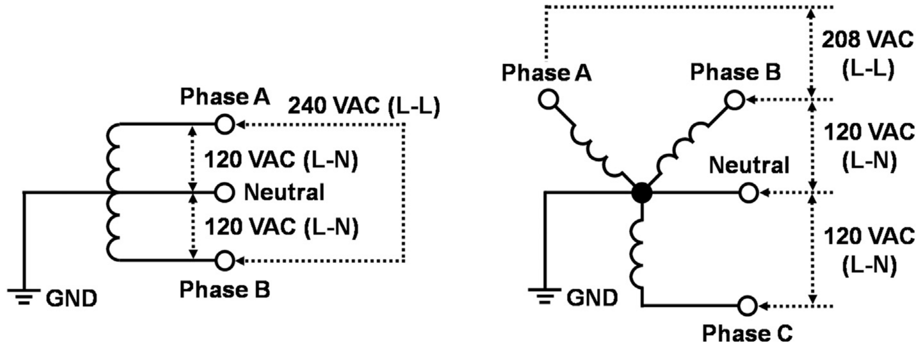

Fig. 8 – Single phase, 3-wire 120/240 VAC service (left) and three phase, 4-wire 120/208Y VAC service (right).

and cooling unit, and heat pump water heater, are electric. The electric load characteristics of the single family home equipped with a 120/240 VAC, 3-wire single phase, 200 A service are summarized in Table 4.

In Table 4, the standard electrical appliances in a single family home include an electric cooktop, electric oven, clothes dryer, clothes washer, refrigerator, dishwasher, microwave, as well as lighting and household electronics such as television set(s) and computer(s). Among the standard electrical appliances, the electric cooktop, electric oven and electric clothes dryer have the largest power ratings using 240 VAC with 40 A, 20 A and 30 A circuit breakers, respectively. The electric cooktop is assumed to be a Viking model VEC5304B unit comprising 4 electric burners or hot plates that seldom operate with a total current approaching 40 A, since not all 4 hot plates are enabled simultaneously. The electric oven is assumed to be a GE model ZET1PHSS unit. The electric cooktop and oven are each used for at most 2 hours per day at a mean power level of 1800 W and 2850 W, respectively for cooking food, resulting in a mean energy consumption of 100.8 kWh/month and 159.6 kWh/month, respectively. The electric dryer is assumed to be a Whirlpool model WED90-HEFW unit with an EPA Energy Star estimated annual energy use of 608 kWh, corresponding to a mean energy consumption of 50.7 kWh/month. The clothes washer is assumed to be a Whirlpool model WFW92HEFW unit with an EPA Energy Star estimated annual energy use of 89 kWh, corresponding to a mean energy consumption of 7.4 kWh/month. The refrigerator is assumed to be a GE model GSE22ESHSS unit with an EPA Energy Star estimated annual energy use of 604 kWh, corresponding to a mean energy consumption of 50.3 kWh/month. The dishwasher is assumed to be a Whirlpool model ZDT975SPJSS unit with an EPA Energy Star estimated annual energy use of 270 kWh, corresponding to a mean energy consumption of 22.5 kWh/month. The microwave is assumed to be a GE model ZSC1202JSS unit. The microwave uses 120 VAC with a 20 A circuit breaker and operates for at most 1 hour per week at a mean power level of 1800 W for warming food, resulting in a mean energy consumption of 7.2 kWh/month. The electric lighting in the single family home is assumed to be comprised of efficient LED lamps and consequently, the power drawn by the lighting will not exceed 100 W. The electric lighting operates in the early morning as well as in the evening for a total of 6 hours per day, resulting in a mean energy consumption of 18.2 kWh/month. It is assumed that the household electronics consume the same amount of energy, 18.2 kWh/month, as the electric lighting. Therefore, the total mean monthly energy consumption of the standard household electrical appliances is given as $E_T = 434.9$ kWh/month.

Table 4 – Electric load characteristics of the single family home.

	[a]Voltage [Volts]	[b]Current [Amps]	[c]Energy [kWh/mo]
Electric cooktop	240	40	100.8
Electric oven	240	20	159.6
Clothes dryer	240	30	50.7
Clothes washer	120	20	7.4
Refrigerator	120	20	50.3
Dishwasher	120	20	22.5
Microwave	120	20	7.2
Lighting	120	10	18.2
Household electronics	120	10	18.2
Subtotal			**434.9**
Heat pump heating and cooling unit	240	35	
(Chicago, IL)			729.9
(Boston, MA)			719.8
(El Paso, TX)			604.9
(Miami, FL)			581.3
(Los Angeles, CA)			478.3
Electric heat pump water heater	240	25	152.5
[d]Battery electric vehicle (BEV)	240	40	672
Total			**1737.7–1989.3**

[a] Voltage supplied to house by the hydrogen fuel cell electric generator is 120/240 VAC, 3-wire single phase.
[b] Current values represent ratings of the service panel mounted electric circuit breakers. Operating currents are lower.
[c] Average monthly energy consumption estimates for household appliances are mostly based on data from www.energystar.gov.
[d] BEV charging at 240 VAC and 20 A occurs for 5 hours every night to fully recharge a 24 kWh battery.

Most single family homes in the U.S.A. presently utilize carbon based fossil fuels for heating. In the more remote rural areas, wood burning stoves are common, as are fuel oil or propane based boilers for heating during the cold months of the year. The electric heating and electric cooling needs of single family homes within the conterminous 48 states of the

U.S.A. can also be met reliably using a high efficiency, air source packaged heat pump. In Table 4, it is assumed that the Goodman model GPH1630H41A heat pump with a nominal capacity of 30,000 BTU/hr, operates in five different geographic regions of the U.S.A. each with a different climate to heat and cool a small to medium size home including in Chicago, Illinois; Boston, Massachusetts; El Paso, Texas; Miami, Florida; and Los Angeles, California. In Chicago, Illinois the heat pump cools for 683 hr/year and heats for 2459 hr/year. In Boston, Massachusetts it cools for 729 hr/year and heats for 2397 hr/year. In El Paso, Texas it cools for a total of 1524 hr/year and heats for 1559 hr/year. In Miami, Florida it cools for 3931 hr/year and heats for 265 hr/year. In Los Angeles, California it cools for 1530 hr/year and heats for 1070 hr/year. The total mean monthly electric energy consumption for the GPH1630H41A heat pump is estimated using the energy cost calculator for air source heat pumps provided at the Energy Star website of the U.S. Environmental Protection Agency (EPA), and is given as $E_T = 729.9$ kWh/month for Chicago, $E_T = 719.8$ kWh/month for Boston, $E_T = 604.9$ kWh/month for El Paso, $E_T = 581.3$ kWh/month for Miami and $E_T = 478.3$ kWh/month for Los Angeles [44]. The hot water needs of the single family home can in turn be met using an electric heat pump water heater that is assumed to be a GE model GEH50DEEDSR unit with an EPA Energy Star estimated annual energy use of 1830 kWh, corresponding to a mean energy consumption of 152.5 kWh/month.

Most motor vehicles presently operating in the U.S.A. are fueled with carbon based fossil fuels including gasoline, Diesel and natural gas. If one battery electric vehicle (BEV) such as the 2013 Nissan Leaf described in the section titled Method of application, equipped with a 24 kWh battery is parked in the driveway or garage of the single family home and recharged to capacity from a discharged state within 5 hours every night from a 240 VAC outlet, then the total mean monthly electric energy consumption from charging will be given as $E_T = 672$ kWh/month.

It is evident from the mean monthly electric energy consumption figures given in Table 4 for a small to medium size single family home located within the 48 conterminous states, that to supplant the carbon based fossil fuels presently used disproportionately for home heating and motor vehicle propulsion, would require at least a quadrupling of the total electric energy consumption for the single family home, from $E_T = 434.9$ kWh/month to $E_T = 1989.3$ kWh/month. The hydrogen fuel cell electric generator described in Table 2, based on the 160 cell hydrogen generation apparatus using Na metal and delivering $E_{Na160} = 499.6$ kWh of energy, would be capable of providing the basic energy needs of the single family home that consumes on average $E_T = 434.9$ kWh/month. The hydrogen fuel cell electric generator would then have to be refueled with 482 kg of Na metal, on average once per month throughout the year. If the model GPH1630H41A electric heat pump is used for heating and cooling throughout the year, with the GE model GEH50DEEDSR unit providing hot water, then the total electric energy consumption for the single family home will increase to $E_T = 1317.3$ kWh/month, requiring the hydrogen fuel cell electric generator based on the 160 cell hydrogen generation apparatus to use NaH as described in Table 3, to deliver 1149.6 kWh of energy. The hydrogen fuel cell electric generator would then necessitate refueling with 579 kg of NaH, on average once every 26 days throughout the year. The NaH refueling would occur more frequently during the winter heating season, and less frequently during the summer or the reverse, depending on the geographic location of the single family home.

It is also clear from Table 4, that recharging a BEV such as the 2013 Nissan Leaf equipped with a 24 kWh battery in the garage or driveway of the single family home, will result in a significant increase in the total household electric energy consumption. It therefore becomes essential to incorporate a hydrogen fuel cell electric generator based on the smaller 40 cell hydrogen generation apparatus in the BEV to continuously recharge the battery, not only to provide greater autonomy to the BEV by extending its range, but also to obviate having to frequently refuel the stationary hydrogen fuel cell electric generator based on the 160 cell hydrogen generation apparatus supplying the single family home.

The results of the analysis for energy consumption of a small to medium size single family home geographically located within the 48 conterminous states of the U.S.A., clearly reveal the challenges inherent with attempting to supplant carbon based fossil fuels for home heating as well as motor vehicle propulsion. The hydrogen fuel cell electric generator based on a novel, scalable hydrogen generation apparatus that uses either Na metal or NaH to generate high purity $H_{2(g)}$ fuel on demand according to Eqs. (1) and (7), respectively with a direct, cost effective means to reprocess the NaOH byproduct via solar powered electrolysis according to Eq. (2) to recover the Na metal, represents a key enabling technology for fully supplanting carbon based fossil fuels in powering single family homes and for introducing BEVs into widespread operation.

Electric energy consumption of a light commercial establishment

The energy consumption of a light commercial establishment such as a medium size combination pharmacy and grocery store located within the conterminous 48 states of the U.S.A., supplied by the hydrogen fuel cell electric generator based on the 160 cell hydrogen generation system can be estimated considering that all the commercial refrigeration appliances, lighting, heat pump heating and cooling unit, and heat pump water heater, are electric. The electric load characteristics of the combination pharmacy and grocery store equipped with a 120/208Y VAC, 4-wire three phase service are summarized in Table 5.

In Table 5, the standard electrical appliances in the combination pharmacy and grocery store include up to ten commercial refrigerator units, as well as lighting and electronics such as computer(s). The refrigerator is assumed to be a Frigidaire model FCGM181RQB unit with an EPA Energy Star estimated daily energy use of 2.26 kWh/day, corresponding to a mean energy consumption of 68.6 kWh/month. The microwave is assumed to be a GE model ZSC1202JSS unit. The microwave uses 120 VAC with a 20 A circuit breaker and operates for at most 1 hour per week at a mean power level of 1800 W

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

Table 5 – Electric load characteristics of the combination pharmacy and grocery store.

	[a]Voltage [Volts]	[b]Current [Amps]	[c]Energy [kWh/mo]
Refrigerators	120	20	68.6 (×10)
Microwave	120	20	7.2
Lighting	120	10	327.6
Electronics	120	10	36.4
Subtotal			**1057.2**
Heat pump heating and cooling unit	208	60	
(Chicago, IL)			1459.8
Electric heat pump water heater	208	25	152.5
Total			**2669.5**

[a] Voltage supplied to store by the hydrogen fuel cell electric generator is 120/208Y VAC, 4-wire three phase.
[b] Current values represent ratings of the service panel mounted electric circuit breakers. Operating currents are lower.
[c] Average monthly energy consumption estimates for appliances are mostly based on data from www.energystar.gov.

for warming food, resulting in a mean energy consumption of 7.2 kWh/month. The electric lighting in the combination pharmacy and grocery store is assumed to be comprised of Sylvania-73835 recessed LED lamps that each have a power consumption of 9 W. There are 100 LED lamps in the store that draw a total power of 900 W for 12 hr/day, resulting in an energy consumption of 327.6 kWh/month. It is assumed that the commercial electronics draw a total power of 100 W for 12 hr/day, resulting in an energy consumption of 36.4 kWh/month. Therefore, the total mean monthly energy consumption of the standard electrical appliances in the store is given as $E_T = 1057.2$ kWh/month.

In Table 5, it is assumed that the Goodman model GPH1660H41A heat pump with a nominal capacity of 60,000 BTU/hr, operates to heat and cool the store in Chicago, Illinois. The heat pump cools for 683 hr/year and heats for 2459 hr/year. The total mean monthly electric energy consumption for the GPH1660H41A heat pump is estimated using the energy cost calculator for air source heat pumps provided at the Energy Star website of the U.S. Environmental Protection Agency (EPA), and is given as $E_T = 1459.8$ kWh/month for Chicago. [44] The hot water needs of the store can in turn be met using an electric heat pump water heater that is assumed to be the GE model GEH50DEEDSR unit with an EPA Energy Star estimated annual energy use of 1830 kWh, corresponding to a mean energy consumption of 152.5 kWh/month.

It is evident from the mean monthly electric energy consumption figures given in Table 5 that a medium size store located in Chicago, Illinois, would require a total electric energy consumption $E_T = 2669.5$ kWh/month. The hydrogen fuel cell electric generator described in Table 3, based on the 160 cell hydrogen generation apparatus using NaH and delivering $E_{NaH160} = 1149.6$ kWh of energy, would be capable of providing the comprehensive energy needs of the store. The hydrogen fuel cell electric generator would then necessitate refueling with 579 kg of NaH, on average once every 13 days throughout the year. The NaH refueling would occur more frequently during the winter heating season, and less frequently during the summer in Chicago.

Discussion of results

The analysis of a hydrogen fuel cell electric generator based on a novel, scalable, hydrogen generation apparatus is significant because it affirms the viability of the system to provide electric power with zero noise and emissions as part of a sustainable, closed clean energy cycle in conjunction with self-contained solar powered electrolytic sodium (Na) metal production plants, for a broad range of applications in ground based electric power generation. [17,22] Hitherto, the scientific catechism has maintained that electric power should be generated using large scale hydroelectric, nuclear or coal fueled thermal power plants of 1000 MW or more, and distributed to residential homes, commercial businesses and industrial enterprises through an electric grid. At times of peak electric power demand, natural gas fueled gas turbine or Diesel fueled electric generators coupled to the electric grid can be turned on. In addition, heating for homes and other edifices should be provided using boilers that burn fuel oil, propane or natural gas. In remote rural areas, traditional wood or charcoal burning stoves can be used for home heating.

The fundamental problem with the accepted catechism lies in the fact that hydroelectric generating capacity is a finite resource that has already been developed to its maximum useful capacity in the U.S.A., Europe as well as in many other developed areas of the world [45]. With regard to nuclear power stations, the public has grown justifiably fearful of the dangers posed by the possibility of radiological leaks that depending on their severity, can render wide swathes of land uninhabitable for lengthy periods while in the process destroying lives and livelihoods as has occurred in Chernobyl, Ukraine and Fukushima, Japan [46–48]. The only means left to provide sufficient electric power for the expected proliferation of battery electric vehicles (BEVs) will be from coal fueled thermal power plants that constitute a major source of carbon dioxide (CO_2) emissions and environmental pollution.

We have shown however, that it is possible to construct a sufficient number of self-contained solar powered electrolytic sodium (Na) metal production plants that effectively store the sun's radiant energy as Na metal, in the southwestern U.S.A., to supply the hydrogen fuel cell electric generator described, on a scale needed to fully obviate the need for carbon based fossil fuels in motor vehicles. [22] The solar powered Na metal production plant capacity can be expanded further to also provide for ground based electric power generation for single family homes and light commercial establishments of the type described in the sections titled Electric energy consumption of a single family home and Electric energy consumption of a light commercial establishment. Our company believes that solutions beyond power distribution systems centered on the electric grid are needed, according to the sustainable hydrogen clean energy paradigm described, to engender a safe, reliable and permanent transition to renewable clean energy in the U.S.A. and throughout the world.

Conclusion

The hydrogen fuel cell electric generator based on a novel, scalable, hydrogen generation apparatus has been shown capable of providing electric power with zero noise and emissions for myriad applications that have traditionally depended on carbon based fossil fuels. The primary problem with using carbon based fossil fuels exists due to the high levels of atmospheric pollution they engender, including emissions of carbon monoxide (CO), an immediate threat to human health and carbon dioxide (CO_2), a delayed threat to the global climate. A secondary problem occurs due to the fact that liquid hydrocarbons used for motor vehicle transport applications, constitute a finite resource which is not uniformly distributed on the planet. Thus, from both an environmental as well as geostrategic resource perspective, it is beneficial to supplant carbon based fossil fuels in ground based energy generation. By contrast, the vast radiant energy emission produced by hydrogen fusion in the sun is a more uniformly distributed energy resource on the planet accessible in great abundance along latitudes near the tropics. The new sustainable hydrogen clean energy paradigm represents in all regards a superior solution to the carbon based fossil fuel systems that it aims to supplant by introducing advanced technology of a new type, offering improved safety through the use of nonvolatile solid sodium metal as an energy carrier, noise free operation with zero emissions, and the potential to be more cost effective by using renewable energy from the sun to recycle high energy materials.

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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