

Producing drinking water from hydrogen fuel cells

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ABSTRACT

In a future hydrogen economy, harvesting water from H₂ fuel cells and other devices should be considered as a by-product of their operation. We hypothesize that the water quality produced by modern fuel cells is higher than typical tap waters and complies with US Environmental Protection Agency (USEPA) regulations. Water samples were collected from six different fuel cells (FCs) operated at research centers across the US, and their constituents were measured. The water quality parameters were below the maximum contaminant levels except for zinc, lead and antimony, which may be related to plumbing or FC material leaching. To investigate the yield of water from FCs, water to energy production ratios were modeled. With 85% capture of exhaust water, an FC operating to meet daily energy consumption needs of a typical US household would produce ~16 L of water. This is nearly the volume of internal human consumption of water, but far less than the ~410 L/capita/d of total potable water demand which accounts for all uses of water. In a nationwide hydrogen economy, where all energy consumed comes from hydrogen, over 4.9 billion m³ of high quality water per year would be produced as by-products of hydrogen usage.

Key words | fuel cell, hydrogen economy, potable water, water quality

INTRODUCTION

Water and energy production and demand are interconnected (US Department of Energy 2006). Coal, natural gas and nuclear thermoelectric power plants, steam-driven turbine generators and evaporative cooling systems consume water. The US consumes approximately 200 billion gallons per day to produce electrical energy, excluding hydroelectric power (USGS 2006). In 2006, thermoelectric power generation accounted for 48% of the total water use in the United States (USGS 2006). Transport of water for all uses consumes up to 20% or more of the total electricity in many states. Energy is also consumed in the conveyance of raw water, treatment and distribution of potable water. Therefore, energy essentially contains “embedded water”, or “virtual water” and water contains “embedded energy” (Zimmerman *et al.* 2008). Infrastructure systems should consider not only reducing water usage

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during energy production, but potentially recovery of high quality water at distributed sources for potable consumption.

Today's drinking water technologies (membranes, advanced oxidation, etc.) focus on removing contaminants to produce water suitable for home and industrial applications. These processes, besides being energy-intensive, often generate unwanted by-products (e.g. brines) that may require management. However, with clean water and energy becoming ever more precious commodities, generating potable water is likely to become more expensive. Therefore, one must think “out-of-the-box” to provide novel alternatives that use new technologies to generate water of potable quality. This paper evaluates the feasibility of generating potable water from one specific technology, hydrogen fuel cells, which are projected to become a readily

commercially available technology within a decade, and which may be part of a broader hydrogen economy (Larminie & Dicks 2003; Barclay 2006). This paper does not represent a Life Cycle Assessment (LCA) study, but rather it focuses on the technical aspects related to water quality and yield of generating potable water from common types of fuel cells.

The majority of hydrogen produced today comes from petroleum-based products or electrolysis of water (Larminie & Dicks 2003). Hydrogen fuel cells electrochemically convert hydrogen and oxygen into electricity and water. Although a variety of hydrogen fuel cells exist, this paper focuses on one type, polymer electrolyte membrane fuel cells (PEMFC). These fuel cells are the most widely used because of their high power density (the highest of any fuel cell), ability to quickly respond to changes in current demand, low operating temperature and relatively low cost (Mehta & Cooper 2003). Figure 1 shows the components of a typical PEMFC and its general operating principles. As illustrated, PEMFCs contain a polymer membrane electrolyte with two electrode plates on either side that serve as cathode and anode. The membrane allows only migration of protons. It is impermeable to electrons, which are transported from the anode to the cathode via an external circuit, and to gases, which are present at both electrodes. The anode and cathode are coated with a catalyst (usually platinum), which enables low temperature dissociation of hydrogen gas into two protons and two electrons as well as their recombination with oxygen to produce water (Larminie & Dicks 2003; Mehta & Cooper 2003; Barclay 2006).

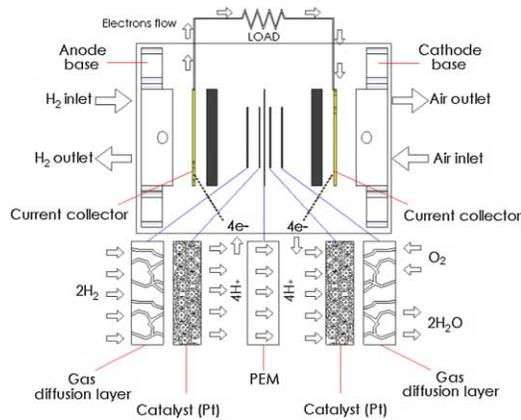


Figure 1 | Components of a typical polymer electrolyte fuel cell.

Fuel cells generate only water and energy. Although the water should be pure, impurities in the hydrogen and air supplied to the electrodes, as well as the deterioration of the membrane and fuel cell materials, may result in the presence of contaminants in the water generated from fuel cells (Collier *et al.* 2006; Chen *et al.* 2007). Another factor contributing to the presence of contaminants in the generated water may be the external water supplies which are often used as a source of humidification. Polymer membranes must stay hydrated for proton conductance. Fuel cell reactants can be humidified (using an external water supply or reclaimed fuel cell water) or the membrane can be self-humidified, requiring no ancillary humidification equipment (Watanabe *et al.* 1996).

A literature review on fuel cells indicates that only a few older studies focus on water quality. In 1962, the Gemini space program made efforts to use fuel-cell-generated water as onboard drinking water for astronauts. However, the alkaline fuel cells with organic electrodes generated water that contained sulfobenzoic acid, *p*-benzaldehyde sulfonic acid and formaldehyde (Collier *et al.* 2006). This problem was resolved during the Apollo space program when the organic electrodes were replaced with sintered nickel. The modified fuel cells produced water at a peak rate of 1 L/h with a quality close to that of distilled water. The exception was the presence of a bis(pentamethylenedithiocarbamate) Ni(II), which appeared after the water was stored in water storage tanks of the space module (Richard & Davis 1975). In 1998, Orta *et al.* (1998) conducted a study focusing on the quality of the water generated by the fuel cells aboard the Space Shuttle and the Mir Space Station. According to the report, both waters were the same quality as distilled water, with only a few anions and cations at $\mu\text{g/L}$ concentrations. Fuel cell technology has evolved dramatically over the past few decades (Tawfik *et al.* 2007) and there have been no studies on the quality of water produced from these newer types of fuel cells.

Based on the existing data, we hypothesize that the quality of water produced by modern fuel cells is higher than typical tap waters and complies with US Environmental Protection Agency (USEPA) regulations. To validate our hypothesis, we analyze the quality of water samples collected from six hydrogen fuel cells in North America and compare the data to municipal water quality

parameters and USEPA maximum contaminant levels (MCLs). We also use Fenton's reagent in a membrane leaching test to study the impact of membrane degradation on water quality. Additionally, we model water yield based on data from existing literature and commercially available fuel cells. This is not a Life Cycle Assessment (LCA) study, but the results should be incorporated into future LCA analyses involving the H₂ economy.

RESEARCH METHODS

Water samples were obtained from six laboratory-scale PEMFCs operated at research centers across the United States. Samples from different fuel cells were obtained to provide randomness which would not have been exhibited if samples were collected from a single fuel cell operated under specific conditions. It must be noted that the goal of this study was not to evaluate the impact of operating conditions on water quality, but rather to examine and investigate the overall concept of producing drinking water from hydrogen fuel cells. A study that examines the impact of operating conditions on water quality is being currently conducted at Arizona State University.

The exhaust water generated at the cathode and the inlet water used for humidification of the hydrogen (where applicable) were collected for analysis. The samples were transported and stored in accordance with procedures described in *Standard Methods for Examination of Water*

and *Wastewater* (Franson *et al.* 1995) and were analyzed immediately upon their reception to reduce sample impairment. Table 1 presents descriptions of the fuel cells and their performance parameters. We do not list some specific information, such as research group or fuel cell model, in accordance with an internal agreement to keep this information confidential.

Fenton's reagent leaching test (Healy *et al.* 2005; Collier *et al.* 2006), which simulates the most severe conditions to which a membrane may be exposed inside a fuel cell and thus yields the maximum water contamination from membrane chemical degradation, was performed on one of the most widely used fuel cell membranes—Nafion 111-IP (Ion Power Inc.) This test (described in the supporting information, available online at <http://www.iwaponline.com/jws/058/0003.pdf>) is the most commonly used laboratory test to study the degradation of membranes because it is a good source of hydroxyl radicals (Chen *et al.* 2007). The major anions, pH and TOC of the leachates were analyzed.

The water quality analysis consisted of measuring pH (Beckman 250), conductivity (Thermo Orion 130A), total organic carbon (Shimadzu 5050A TOC, MDL 0.5 mg TOC/L) and concentrations of the major anions and cations using ion chromatography (Dionex DX-120) and inductively coupled plasma mass spectroscopy (Thermo Electron Element 2, MDL < 1 µg/L), respectively. QA/QC procedures included analysis of quality control samples and laboratory-blank samples. Only

Table 1 | Description of the fuel cells used in the study

Fuel cell location	Colorado	Delaware	Hawaii	Connecticut	New York	Arizona
Fuel cell type	PEM	PEM	PEM	PEM	PEM	PEM
Membrane	Nafion 112	Proprietary	Nafion NRE 212	Proprietary	Polybenz imidazole based	Nafion 112
Fuel	H ₂	H ₂	H ₂	H ₂	H ₂	H ₂
Oxidant	O ₂	Air	Air	Air	Air	Air
Electrode material	Carbon cloth	Proprietary	SIGARCET	Carbon cloth	Carbon cloth	Carbon cloth
End plate material	Graphite	Proprietary	Al	Au-coated metal	Stainless steel	Graphite
Operating temperature (°C)	80	70	80	85	160	33
Inlet humidification	DI water	Unknown water	DI water	DI water	No humidification	No humidification
Membrane area (cm ²)	5.48	375	100	29.4	45.15	25
Operating current density (mA/cm ²)	500	533	1,000	1,000	200	12

samples that exhibited Relative Standard Deviation (RSD) < 5% were accepted.

EXPERIMENTAL RESULTS

The USEPA has MCLs for contaminants that pose major health hazards and nonenforceable standards (SMCLs) as guidelines for unpleasant odors or colors. Table 2 compares the pH, conductivity and major anion concentrations that were obtained for the evaluated waters to the MCLs and SMCLs. This table also compares the fuel cells' water quality results to the averaged water quality parameters obtained from reports or analysis of municipalities in different parts of the US.

The pH values of all fuel cell samples were lower than the SMCLs and that of the municipal waters. The inlet waters used for hydrogen humidification all exhibited pH values lower than 6.2, while the outlet waters exhibited pH values lower than 6.1. These low pH values correspond well with those of waters that exhibit high purity and low alkalinity, but are left to equilibrate with atmospheric CO₂. The high purity of all samples is also indicated by their very low conductivities, which were one to two orders of magnitude lower than that of the municipal water or the SMCLs. The pH, conductance and ionic composition of water influence the corrosivity of water toward piping materials (Edwards & Trianrafyllidou 2007). Metal components (copper, brass, iron, lead soldering, etc.), which are

part of a fuel cell system, can easily corrode due to metal dissolution over a period of prolonged exposure to aggressive waters (low, conductance, alkalinity, pH, etc.).

Organics in drinking are a concern because of potential direct health effects or byproducts of their reactions with disinfectants. Figure 2 presents the TOC concentrations of the evaluated waters; the amounts of TOC in the samples were lower than or similar to that of the reference municipal water, except for the water generated by the Arizona fuel cell, which exhibited 20 times more TOC, and the Delaware exhaust water, which probably contained high TOC as a result of the inlet water. The figure suggests a general trend, namely that the exhaust waters exhibit higher TOC concentrations than the inlet humidification waters, except for the Connecticut fuel cell. This presence of TOC in the exhaust water could be due to fuel cell membrane/electrode degradation or the presence of organic materials in the air used as an oxidizer. The inlet water for the Delaware fuel cell exhibited almost the same TOC concentration as the exhaust water, suggesting that TOC in the exhaust water may be a result of humidification water quality. In contrast, the Arizona fuel cell did not involve humidification, so the increased TOC concentration of its exhaust water is probably due to decomposition of the organic membrane, diffusion/catalyst layer or of water-soluble organic carbon trapped from the feed air which is used as an oxidant in the fuel cell.

Table 2 also summarizes the concentrations of major anions present in the fuel cell waters and compares these

Table 2 | pH, conductivity and major anions present in the evaluated fuel cell waters expressed as meq/L

Aggregate parameter or anion	US EPA	Reference municipal	Colorado		Delaware		Hawaii		Connecticut		New York	Arizona
		water [§]	In [†]	Out [†]	In	Out	In	Out	In	Out	Out	Out
pH	6.5–8.5	7.6	5.7	6.1	5.5	5.6	6.2	4.6	5.5	5.4	4.6	4.1
Conductivity (μS/cm)	1,000 [‡]	578.2	4.4	23.4	8.8	4.6	16.8	16.6	1.9	2.5	15.8	97.7
F ^{-§} (meq/L)	4	0.049	0.006	0.064	0.002	0.003	0.002	0.016	0.001	0.004	0.026	0.041
Cl ⁻ (meq/L)	250	2.05	0.123	0.127	0.160	0.108	0.097	0.131	0.097	0.119	0.131	0.613
SO ₄ ²⁻ (meq/L)	500	0.612	0.149	0.178	0.152	0.168	0.148	0.148	0.147	0.147	0.149	0.204
NO ₂ ^{-§} (meq/L)	3	NA	0	0.002	0	0	0	0	0	0	0	0
NO ₃ ^{-§} (meq/L)	44	0.062	0.002	0.002	0	0	0	0	0	0	0	0
PO ₄ ³⁻ (meq/L)	NA	0.014	0.001	0.001	0.003	0.003	0.001	0.001	0.001	0.001	0.011	0.004

^{*}See Table S11 in the supplemental information for reference municipal tap water. Available online at: <http://www.iwaponline.com/jws/058/0003.pdf>

[†]In: inlet water; Out: exhaust water.

[‡]Conductivity (μS/cm) = 2 × TDS (mg/L) (Crittenden et al. 2005).

[§]MCL.

^{||}SMCL.

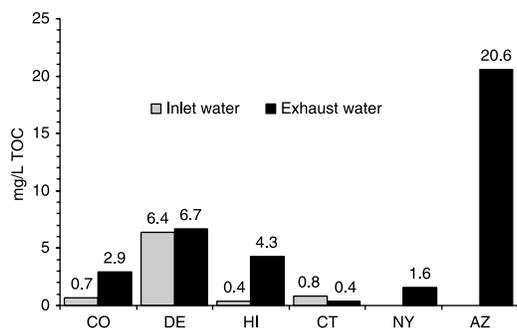


Figure 2 | Total organic carbon (TOC) present in the studied fuel cell waters (See Table S11 in the supplemental information for reference municipal tap water with an average TOC of 3.6 mg/L. Available online at: <http://www.iwaponline.com/jws/058/0003.pdf>).

with the current MCLs and SMCLs as well as the values obtained for municipal tap water. All PEMFC waters exhibited anion concentrations that were at least one order of magnitude lower than the MCLs and the municipal water values. The data in Table 2 shows an interesting trend regarding fluoride and sulfate. Fluoride concentrations were uniformly higher in the exhaust water than in the inlet water, while sulfate exhibited either the same or higher concentrations in exhaust water as compared to inlet water. We attribute this release of fluoride and sulfate ions into the exhaust water to the probable deterioration of the polyelectrolyte membrane. In the batch membrane degradation tests with Fenton's reagent, fluoride and sulfate are extensively released during deterioration of the membrane (Figure 3). More than 1.6 mg/L ($\sim 85 \mu\text{eq/L}$) of fluoride and 2.4 mg/L ($\sim 50 \mu\text{eq/L}$) of sulfate were released per cm^2 of membrane after 24 h contact with Fenton's reagent. In contrast, the fluoride and sulfate concentrations leached from the membrane which was soaked only in DI water were ≥ 50 and > 8 times lower, respectively. Furthermore, the membrane decomposition released $> 250 \mu\text{g/L}$ per cm^2 of TOC when exposed to Fenton's reagent. These results from the Fenton's reagent tests were anticipated, considering that the Nafion 111-IP membrane is comprised of fluorinated aliphatic carbon chains containing sulfonate groups (Collier *et al.* 2006). The other anions and TOC released from the membrane can be attributed to impurities in the membrane.

Table 3 presents the concentrations of the analyzed cations, some of which are relatively high. In particular, high levels of Pb, Sn and Zn were found in the Delaware, Arizona and Colorado fuel cell waters, respectively. All other fuel cells

exhibited cation concentrations that were lower than the established MCLs. The lead concentration in the Delaware fuel cell exhaust water was seven times greater than the MCL of $15 \mu\text{g/L}$; this is likely due to the relatively high concentration of lead in the Delaware inlet water ($C_{\text{Pb-inlet}} = 73 \mu\text{g/L}$) or the corrosion of lead from solder or copper pipes in the fuel cell system that are often used in fuel cell plumbing (Edwards *et al.* 1995). The antimony concentration in the Arizona fuel cell water was slightly higher than the SMCL of $5 \mu\text{g/L}$; the source of antimony in these samples is unknown but was not present in lab blanks. The Colorado fuel cell water exhibited $7,200 \mu\text{g/L}$ of Zn, which is substantially higher than the SMCL of $5,000 \mu\text{g/L}$. Considering that the inlet water exhibited a Zn concentration of $11 \mu\text{g/L}$, it is reasonable to attribute the high Zn concentration in the exhaust water to fuel cell construction materials, operating conditions or the feed air used as an oxidizer. The Pt concentrations were generally $< 0.7 \mu\text{g/L}$, except for the Arizona fuel cell which exhibited $\sim 8 \mu\text{g Pt/L}$. Such a high concentration of Pt in the exhaust water suggests decomposition of the catalyst layer, which is often comprised of carbon material in addition to Pt. This observation is further supported by the elevated TOC levels in the Arizona water.

Many new fuel cell systems do not require external water sources for humidification. One example of this is a residential-scale fuel cell system (I-100 by ReliOn, Spokane, WA) that is currently running near our facility. The only inputs are ambient air and hydrogen. The system produces electricity and water. The conductance of the water ranges

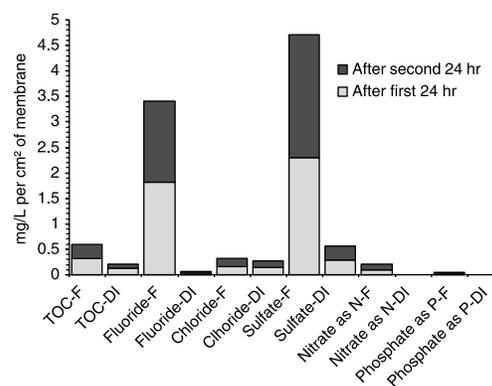


Figure 3 | Total organic carbon and major anions leached as a result of membrane decomposition during Fenton's test (-F indicates use of Fenton's reagent; -DI indicates use of DI water).

Table 3 | Major cations present in the evaluated fuel cell waters

Cation ($\mu\text{g/L}$)	US EPA	Reference municipal	Colorado		Delaware		Hawaii		Connecticut		New York	Arizona
		water*	In [†]	Out [†]	In	Out	In	Out	In	Out	Out	Out
Sb [‡]	6	≤ 3.0	0.03	0.19	0.31	0.39	0.04	0.18	0.02	0.03	0.03	7.72
As [‡]	10	≤ 3.5	0.01	0.16	0.03	0.06	0.01	0.01	0.00	0.01	0.00	0.08
Ba [‡]	2,000	41	0.72	2.14	3.07	2.06	1.57	1.82	0.31	1.46	1.72	36.70
Be [‡]	4	< 4.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Cd [‡]	5	< 5.0	0.01	0.25	0.05	0.08	0.02	0.09	0.21	0.01	0.02	1.51
Cr [‡]	100	≤ 50.0	0.05	19.00	0.16	0.07	0.26	0.84	0.06	0.35	3.00	3.01
Ni [§]	100	< 5.0	19.80	6.50	2.38	10.70	3.80	8.56	1.15	0.19	2.90	79.0
Se [‡]	50	< 5.0	0.00	0.01	0.01	0.03	0.02	0.00	0.00	0.00	0.01	0.08
Th [§]	2	≤ 5.0	0.00	0.04	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01
Pb [‡]	15	≤ 9.2	0.03	0.89	73.00	107.20	0.37	0.28	0.12	0.05	0.18	13.20
Cu [§]	1,300	48	0.52	6.90	371	606	4.80	2.75	0.62	0.68	9.30	71.50
Fe [§]	300	75	0.31	5.30	2.70	1.88	3.80	38.80	0.24	0.27	26.30	44.10
Mn [§]	50	< 5.00	0.09	7.00	0.57	4.15	7.80	3.79	0.14	0.88	0.52	7.50
Ag [§]	100	< 2.00	0.00	0.04	0.03	0.06	0.07	0.01	0.01	0.01	0.02	0.8
Zn [§] (mg/L)	5	< 0.022	0.011	7.20	0.255	0.860	0.136	0.023	0.005	0.032	0.011	0.211
Pt	NA	NA	0.01	0.41	0.39	0.69	0.01	0.01	0.01	0.02	0.01	8.2

*See Table S11 in the supplemental information for reference municipal tap water. Available online at: <http://www.iwaponline.com/jws/058/0003.pdf>

[†]In: inlet water; Out: exhaust water.

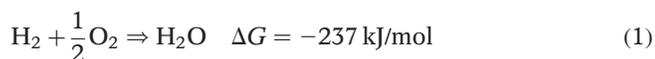
[‡]MCL.

[§]SMCL.

between 3 and 10 $\mu\text{S/cm}$, indicating similar quality as the laboratory waters from the fuel cells presented above.

MODELING WATER YIELD FROM FUEL CELLS

Hydrogen fuel cells are based on a simple chemical reaction in which oxygen oxidizes hydrogen to produce water:



The liquid water flow rate Q_W produced by the fuel cell can be expressed by (2) (Buie *et al.* 2006):

$$Q_W = \frac{j \times A_{\text{FC}} \times M_W}{2 \times F \times \rho_W} \quad (2)$$

where ρ_W is the density of water (1 g/cm^3); M_W is the molecular weight of liquid water (18 g/mol); j is the current density (A/cm^2); A_{FC} is the area of the fuel cell (cm^2) and F is Faraday's constant ($96,450 \text{ C/mol}$). Typically, the water leaving the fuel cell exits as both a liquid and vapor, depending on the operating current, temperature and level

of gas reactant humidification in the fuel cell. Many membranes are now self-humidifying (Watanabe *et al.* 1996) or use reclaimed fuel cell product water, which eliminates external water supplies as a source and potential contaminant.

Equation (2) can be used to calculate the daily water generation of a commercially available fuel cell. An existing commercially available fuel cell stack manufactured by Ballard Power Systems Inc. (Mark1020 ACS) and comprised of a stack of 46 PEM membranes operating at realistic conditions (electric current of 52 A and fuel cell stack power of 1.63 kW) can generate approximately 19 L of water per day, assuming 100% water capture and operating at maximum power demand (Ballard Power Systems Inc. 2008). However, in Chu & Jiang's (1999) work, they were able to capture less than 70% of the effluent water under STP conditions due to evaporation and other losses. Use of condensers should increase the fraction of water captured. If 85% of the water can be captured, this Ballard fuel cell stack could produce the daily internal

consumption of potable water needs of a typical US household as either the primary or supplementary source (cooking and drinking), assuming that an average US household consumes 16 L of water daily (Aquacraft Inc. 1999). The per capita water demand of potable water for all uses, including internal consumption, bodily contact, washing, outdoor use, commercial activities, fire fighting, etc., is greater than 410 L/d; internal consumption is a very small fraction of the total daily use of potable water (Zimmerman *et al.* 2008). Additionally, by running the fuel cell at maximum power to generate sufficient water quantity could yield excess electricity generated as a result of lower household power demand. This excess electricity could be sold to the power utility.

To further evaluate the relationship between daily water and electrical energy requirements, one can calculate a ratio between the water (L) and power (kWh) generated by a fuel cell. For the Ballard fuel cell stack, the water/energy ratio is ~ 0.50 L/kWh, assuming 100% water capture and peak performance for producing power. Figure 4(a) presents a plot of the estimated power and water production based on the Ballard fuel cell mentioned above. This plot shows water production increases linearly with current density, while the fuel cell power increases to a maximum and then decreases. Once the maximum power is reached, the fuel cell will produce more water but with decreasing power output. The power decreases because of the well-known reduction in fuel cell potential (polarization curve) at higher currents. A fuel cell can also be operated under conditions that produce more water and less power. However, if the fuel cell is operated to produce large flows of water (e.g. 900 mL/h), the resulting lower-than-maximum power may render the fuel cell unsuitable to provide electricity for household appliances. Figure 4(b) provides a plot of the water/energy ratio as a function of current density. The ratio increases linearly with current density until approximately 0.9 A/cm², at which point the ratio increases exponentially due to the strong decrease in fuel cell power at high current densities (as shown in (a)). Typically, a fuel cell is operated at its peak power output, which corresponds to a current density of ~ 1 A/cm², which results in a ratio of ~ 0.5 L/kWh for the Ballard fuel cell.

The ratio between the average daily US household drinking water and electricity consumptions is approximately

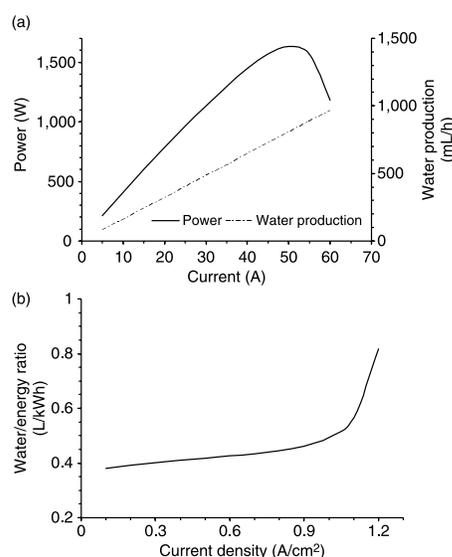


Figure 4 | (a) Plot of power and water production rate of a fuel cell. The fuel cell behavior is estimated from published values of a Ballard Mark1020 ACS fuel cell considering the total power produced by the entire fuel cell stack. The water production increases linearly with the fuel cell current. The power increases to a maximum and then decreases due to losses in the fuel cell voltage. A fuel cell can be run at conditions that produce more water at the expense of energy, as shown for currents in excess of 45 A. (b) Plot of the water/energy ratio as a function of current density. The ratio increases linearly with current density up to approximately 0.9 A/cm², where the ratio increases exponentially. The exponential increase is due to the strong decrease in fuel cell power at high current densities (as shown in (a)).

~ 0.55 L/kWh, using an average daily US household electricity consumption of 29 kWh (US Department of Energy 2008). A comparison of these two ratios suggests that fuel cells operating at their peak power conditions can, on average, fulfill nearly all of a US household's potable internal-consumption water needs, assuming use of a water condensation system and collection of all water. However, on-site storage would be needed to match the supply and demand.

Currently, the production of energy consumes water. Nuclear and coal-fired power plants consume 2–4 L/kWh for cooling and steam generation for every generated kWh of electricity (Aden 2007). In contrast, the fuel cell water to energy ratio is positive because both water and energy are produced. Complete life-cycle assessments on water use for hydrogen production (refinement of petroleum source, electrolysis, etc.) versus release of water and water vapor at the point of use has not been conducted, and is needed in the future.

From a broader perspective, one can estimate the potential for generation of potable water from fuel cells

Table 4 | Estimates of potential for potable water generation in a hypothetical hydrogen economy based on 2005 US energy consumption (see supporting information for details, available online at <http://www.iwaponline.com/jws/058/0003.pdf>)

By sector	Annual US energy consumption in 10 ¹⁵ BTU	Mass of hydrogen to fulfill the annual energy consumption needs of US (10 ⁹ kg)	Water generated at 60% capture in 10 ⁹ m ³ /y (10 ⁹ gal/y)	Water generated in 10 ⁶ m ³ /d (10 ⁶ gal/d)	Water generated in L/capita/d (gal/capita/d)
Industry	35	310	1.7 (440)	4.6 (1.2)	15 (4.1)
Transportation	28	250	1.3 (350)	3.7 (1.0)	12 (3.3)
Commercial	18	160	0.9 (230)	2.4 (0.6)	7.9 (2.1)
Residential	22	190	1.0 (280)	2.9 (0.8)	9.7 (2.6)
Sum	103	910	4.9 (1300)	13.6 (3.6)	45 (12.0)
By fuel type					
Oil	42	370	2.0 (530)	5.5 (1.44)	19 (4.9)
Natural gas	24	210	1.1 (300)	3.1 (0.83)	11 (2.8)
Coal	20	180	1.0 (250)	2.6 (0.69)	8.8 (2.3)
Sum	86	760	4.1 (1080)	11 (3.96)	39 (10.0)

assuming an already established hydrogen economy. Based on 2005 data from the National Research Council for the US primary energy consumption (NRC & NAE 2004), estimates provided in Table 4 suggest that approximately 45 L/capita/d or 4.9 billion m³/y of potable water could be generated in the US if the entire US energy generation was based solely on hydrogen, and water recovery was only 60%. Although less than 10 L/capita/d of water could be generated as a result of hydrogen uses in residential settings, more than 30 L/capita/d could be generated from hydrogen uses in commercial, transportation and industry settings. Additionally, approximately 38 L/capita/d could be generated assuming a type of hydrogen economy where only the nonrenewable energy sources (coal, oil and natural gas) are replaced by hydrogen (Table 4). The suggested estimates in Table 4 indicate that substantial quantities of water with high quality could be generated as a result of hydrogen use.

CONCLUSIONS

The overall results of this study indicate that water generated from fuel cells is relatively pure, with contaminant levels lower than the MCL values. Exceptions to this trend were exhibited by the Delaware and Arizona fuel cell waters, which were characterized by lead and antimony concentrations, respectively, higher than the MCL values. These could likely be overcome by using compatible piping materials, providing simple point-of-use treatment systems

such as GAC cartridges, or modifying fuel cell materials. However, the low conductance of the collected fuel cell water raises a point that this water may be “safe” but remains highly corrosive towards metals. Analysis of the inlet humidification water indicated that the quality of this water can adversely impact the overall water quality. In many cases, the similarities between the water quality parameters of the inlet and exhaust waters suggested that the inlet water contributed the contamination. In addition, low pH values between 4.5 and 6 are often associated with pure waters with low buffering capacity (i.e. alkalinity), which have lower pH due to CO₂ dissolution and formation of carbonic acid.

Based upon a modeling analysis and literature review, residential fuel cells can produce nearly the appropriate amount of water to meet internal human-consumption water needs as either the primary or supplemental source. Storage of this water would be required because energy and water demands may not be correlated. The water yield from residential fuel cells alone would not be sufficient to meet the non-internal consumptive use of water, which is over 25 times greater than the internal human-consumption demand. In a broader hydrogen economy, and not one limited to residential fuel cells, the production of water from hydrogen would yield roughly 1,300 billion gallons/y or more of high quality water suitable for potable use assuming only 60% capture (Table 4). This water quantity dwarfs the 7.5 billion gallons of bottled water produced in 2005 by the US beverage industry (International Bottled Water

Association 2008). Additionally, this water may not only be used for potable uses, but all water should be collected and conveyed to a wastewater treatment facility where it can be partially reused. Another benefit of water production in a future hydrogen economy relates the simultaneous input of energy and water from a production location to urban centers, which in the case of water may preclude necessities to pipe water hundreds of miles or from sensitive aquatic ecosystems. Recovered fuel cell water would be a new paradigm for simultaneous water and energy importation. This may be especially advantageous for inland communities where low-conductance water supplies are becoming a central element for sustainable water resources. Future life cycle assessments and consideration of a hydrogen society should involve the benefits of producing water of high quality as a by-product of hydrogen consumption.

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REFERENCES

- Aden, A. 2007 Water usage for current and future ethanol production. *Southwest Hydrol.* **6**(5), 22–23.
- Aquacraft, Inc. 1999 *Residential End Uses of Water*. American Water Works Association Research Foundation. Available at: <http://www.aquacraft.com/Publications/resident.htm> (retrieved March 15, 2008).
- Ballard Power Systems Inc. 2008 Mark-1020 ACS[®]. Available at: http://www.ballard.com/Backup_Power_Fuel_Cells/Specification_Sheets.htm (retrieved March 15, 2008).
- Barclay, F. J. 2006 *Fuel Cells, Engines and Hydrogen—An Exergy Approach*. John Wiley & Sons Ltd., Chichester.
- Buie, C., Posner, J. D., Fabian, T., Cha, S. K., Eaton, J. K., Prinz, F. & Santiago, J. G. 2006 Active water management for proton exchange membrane fuel cells using an integrated electroosmotic pump. *J. Power Sources* **61**, 191–202.
- Chen, C., Levitin, G., Hess, D. & Fuller, T. 2007 XPS investigation of Nafion[®] membrane degradation. *J. Power Sources* **169**(2), 288–295.
- Chu, D. & Jiang, R. 1999 Comparative studies of polymer electrolyte membrane fuel cell stack and single cell. *J. Power Sources* **80**(1–2), 226–234.
- Collier, A., Wang, H., Ziyuan, X., Zhang, J. & Wilkinson, D. 2006 Degradation of polymer electrolyte membranes. *Int. J. Hydrogen Energy* **31**(13), 1838–1854.
- Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J. & Tchobanoglous, G. (eds) 2005 *Water Treatment: Principles and Design*, 2nd edition. John Wiley & Sons, Inc., New York.
- Edwards, M. & Triantafyllidou, S. 2007 Chloride-to-sulfate mass ratio and lead leaching to water. *J. AWWA* **9**(7), 96–109.
- Edwards, M., Ferguson, J. F. & Reiber, S. H. 1995 The pitting corrosion of copper. *J. AWWA* **86**(7), 74–90.
- Franson, M. A. H., Eaton, A. D., Clesceri, L. S. & Greenberg, A. E. (eds) 1995 *Standard Methods for the Examination of Water and Wastewater*, 19th edition. American Public Health Association, Washington, DC.
- Healy, J., Hayden, C., Xie, T., Olson, K., Waldo, R., Brundage, M., Gasteiger, H. & Abbott, J. 2005 Aspects of the chemical degradation of PFSA ionomers used in PEM fuel cells. *Fuel Cells* **5**(2), 302–308.
- International Bottled Water Association 2008 Bottled Water Continues as Number 2 in 2007. Available at: http://www.bottledwater.org/public/Stats_2007.doc (retrieved July 21, 2008).
- Larminie, J. & Dicks, A. (eds) 2003 *Fuel Cell Systems Explained*, 2nd edition. John Wiley & Sons, Ltd., Chichester.
- Mehta, V. & Cooper, J. 2003 Review and analysis of PEM fuel cell design and manufacturing. *J. Power Sources* **114**(1), 32–53.
- National Research Council & National Academy of Engineering (NRC & NAE) 2004 *The Hydrogen Economy—Opportunities, Costs, Barriers, and R&D Needs*. National Academies Press, Washington, DC.
- Orta, D., Mudgett, P. D., Ding, L., Drybread, M., Schultz, J. R. & Sauer, R. L. 1998 Analysis of water from the Space Shuttle and Mir Space Station by ion chromatography and capillary electrophoresis. *J. Chromatogr. A* **804**, 295–304.
- Richard, L. S. & David, J. C. 1975 *Biomedical Results of Apollo—Potable Water Supply*. Rep. No. LC-75-600030; NASA-SP-368. Lyndon Johnson Space Center, Houston, TX.
- Tawfik, H., Hung, Y. & Mahajan, D. 2007 Metal bipolar plates for PEM fuel cell—a review. *J. Power Sources* **163**, 755–767.
- US Department of Energy 2006 *Energy Demands on Water Resources, Report to Congress on the Interdependency of Energy and Water*. Available at: <http://www.netl.doe.gov> (retrieved March 18, 2008).
- US Department of Energy 2008 Residential Energy Consumption Survey. Available at: <http://www.eia.doe.gov/emeu/recs/> (retrieved March 15, 2008).
- US Geological Survey (USGS) 2006 Thermoelectric-power Water Use. Available at: <http://ga.water.usgs.gov/edu/wupt.html> (retrieved April 1, 2008).
- Watanabe, M., Uchida, H., Seki, Y., Emori, M. & Stonehart, P. 1996 Self-humidifying polymer electrolyte membranes for fuel cells. *J. Electrochem. Soc.* **143**, 3847–3852.
- Zimmerman, J. B., Mihelcic, J. R. & Smith, J. 2008 Global stressors on water quality and quantity. *Environ. Sci. Technol.* **42**(12), 4247–4258.