Title

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Journal
Current Applied Physics, 10(2)

ISSN
1567-1739

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Publication Date
2010-03-01

DOI
10.1016/j.cap.2009.11.002

Current Applied Physics 10 (2010) S9–S17

Contents lists available at ScienceDirect

Current Applied Physics

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

On the role of fuel cells and hydrogen in a more sustainable and renewable energy future

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ARTICLE INFO

Article history:
Received 8 December 2008
Accepted 12 June 2009
Available online 12 November 2009

Keywords:
Fuel cells
Hydrogen
Renewable energy
Sustainable energy

ABSTRACT

Fuel cell energy conversion devices and use of hydrogen as an energy carrier have benefited from major technological advancements in recent years. Fuel cells can provide continuous power with extremely low (or zero) criteria pollutant and greenhouse gas emissions from a variety of renewable and fossil fuels that well compliments the relative intermittency of many forms of renewable power. The sustainability of energy conversion is aided by the highly efficient use of limited fossil fuel reserves, of renewable fuels such as biogas, landfill and digester gas, and of waste fuel streams that can be accomplished using a fuel cell system. Hydrogen can play a significant role in that it is one of only a few options that can enable transportable power with zero pollutant and greenhouse gas emissions at the point of use. In addition, hydrogen can be efficiently produced with very low emissions from a variety of renewable and more sustainable primary energy sources such as wind, solar, and nuclear power (by water electrolysis or splitting), from biogases and industrial waste streams, as well as from fossil fuels such as natural gas and coal. While there are many significant technical hurdles to overcome before fuel cell technology can become widely available and while significant investments will be required to enable the widespread use of hydrogen as an energy carrier, recent developments are proving the environmental and energy efficiency performance, diversity, continuous power capabilities, and potential future economic competitiveness of fuel cell and hydrogen technologies that could enable their future contributions to a more sustainable and renewable energy future. The current paper introduces some potential future roles of fuel cells and hydrogen and highlights some work being conducted at the National Fuel Cell Research Center.

1. Introduction

1.1. Challenges of the current paradigm

Energy and its transformation play critical roles in our lives and directly impact every sector of the economy affecting the overall economic and societal well-being. Per capita energy consumption is often correlated with economic and human health. Energy is used in almost every human activity including: transportation, household uses, agriculture, industry and manufacturing, service, buildings, and more. Thus, energy is consumed by us directly, as in transportation and household uses, as well as indirectly by consuming goods that require energy in their production, delivery or preservation.

Power production and energy conversion are also, not surprisingly, the single largest contributors to the environmental challenges we face. Over 85% of our energy needs are met, and will continue to be met in decades to come, through the consumption of fossil fuels (e.g., coal, oil, natural gas). The consumption of these fossil fuels is primarily through combustion processes (e.g., internal combustion engines, gas turbines, boilers), which transform the fuel's chemical energy into other forms of energy for useful purposes. These combustion-based processes, however, lead to emissions of criteria pollutants (e.g., nitrogen oxides, carbon monoxide, hydrocarbons) and greenhouse gases (e.g., carbon dioxide, methane). In addition, these processes, although fine-tuned over several decades of research and development, are still only capable of transforming about 30% of the fuel's chemical energy into useful energy and power. As a result, there is a significant need for alternative methods of energy conversion.

As a result of scientific and public awareness, great strides have been made in reducing the pollution emitted by combustion sources [1]. Regulations and significant advances in understanding and technology have resulted in the production of modern engines, power plants, and furnaces with dramatically reduced emissions. This has yielded significant improvements in air quality in locations where strict regulatory enforcement occurs [2]. However, energy uses, and consequently combustion emissions, continue

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doi:10.1016/j.cap.2009.11.002

to increase as population increases [3]. Combustion emissions remain the major source of urban air pollution leading to respiratory health problems [4], and remain the primary source of greenhouse gas emissions [5].

1.2. Recent technological progress of fuel cells

Fuel cells offer an alternative to combustion that can more efficiently and with lower emissions convert fossil or renewable fuels into electricity. Combustion processes mix and burn fuel and oxidant with random, uncontrolled motion of electrons to produce heat that is subsequently converted to a useful form of energy (mechanical, electrical) through a heat engine. Conversely, fuel cells directly convert fuel chemical energy to electricity with a controlled flow of electrons through electrochemical reactions that keep fuel and oxidant separate. These fundamental differences lead to higher electrical efficiencies (greater than 50% in some simple-cycle cases and greater than 70% in some hybrid cycles [6]). In addition, fuel cells produce near negligible amounts of criteria pollutants [7], while higher efficiency and renewable fuel use reduce carbon dioxide emissions per unit of power produced.

The technological progress of fuel cells has been astounding in recent decades. Recent fuel cell systems have been engineered with sufficiently low cost, and high enough power and energy density to meet increasingly stringent consumer demands in three major application areas: (1) stationary power, (2) transportation, and (3) portable power.

In stationary power applications high temperature fuel cell technology is increasingly being installed in cost-effective distributed combined heating and power applications using both renewable and fossil fuels see e.g., [8,9]. In addition, future use of hybrid high temperature fuel cell-gas turbine systems is likely to significantly contribute to much higher efficiency and much lower emissions coal-based central power plants with carbon sequestration (see e.g., [10,11]).

Transportation applications of fuel cells have included major bus demonstration programs in Europe, Japan and North America, which have proven the high power density of large modern fuel cell engines. In addition, modern high power density fuel cell engines have been introduced into hundreds of prototype passenger vehicles. These vehicles have proven the superior emissions and efficiency performance characteristics of automotive hydrogen fuel cell engines (see e.g., [11–13]).

Fuel cells are also increasingly being applied to portable power applications, especially as battery replacements for cellular phones and laptop computers, but also as portable electricity generators. Direct methanol and other fuel cell technologies have been advanced to the point of use in many demonstration projects that have built thousands of fuel cells in configurations that allow direct use in portable devices. Recent progress in fuel cell portable power applications has shown higher energy density than state-of-the-art batteries see e.g., [14–16].

1.3. Recent advancements of hydrogen technologies

Significant technological advancements in hydrogen production, distribution and storage are required before hydrogen can be considered for widespread use as an energy carrier. Even if/when hydrogen production and storage capabilities are significantly improved, large investments in hydrogen distribution and fueling infrastructure will be required before widespread use is enabled.

Nonetheless, remarkable progress has been made in improving the efficiency and lowering the cost of hydrogen production. Novel fossil-fuel and renewable means of producing hydrogen have recently been able to meet US DOE performance targets [13,18]. In addition, significant progress has been made in hydrogen storage capabilities. Compressed storage has been very successfully demonstrated at 5000 and 10,000 psi, liquid storage has improved, and metal hydride technology has been significantly improved in recent years [17,19]. Some novel methods for hydrogen storage, such as glass microspheres, poly-hydride complexes and alanates have been significantly advanced. In addition, hybrid means of hydrogen storage, for example, combining pressurized storage with metal hydride storage, are beginning to show promise [20].

1.4. Related technological and market developments

In recent years, technology and market developments that are related to the use of hydrogen and fuel cells have occurred. The most prominent development has been the very successful commercial introduction of hybrid battery electric – internal combustion engine technology. Sales of gasoline hybrid vehicles, such as the Toyota Prius, have increased rapidly over the past several years, while future projections estimate an additional 268% increase in sales by 2012. High fuel prices, a desire to reduce dependence on oil imports, and environmental concerns were cited by new car buyers as reasons for hybrid purchases [22]. Additional justification for hybrid vehicles came from prominent studies by Weiss et al. at MIT [23] and General Motors [24]. Both of these studies report that gasoline hybrid and diesel hybrid vehicles offer energy use and carbon emission performance that is in the top tier of all vehicle options analyzed.

While hybrid vehicles provide acceptable personal mobility options that reduce energy and environmental concerns, they are an emissions and fuel use mitigation strategy that provides only a temporary reprieve between traditional vehicles and a better future technology.

The second most prominent development is that of introducing various renewable power and combined cooling heating and power (CCHP) products into the more open electric power generation markets around the world.

The potential and capabilities of various renewable and distributed generation, energy storage and other resources in restructured electric utility markets has significantly expanded in recent years. Renewable and ultra-clean power generation technologies (including wind, solar-thermal, and fuel cells) are increasingly demanded in the marketplace. Some of this has been spurred by Renewable Portfolio Standards (RPS) that require a certain percentage of total electricity demand to be supplied by renewable energy. Many states in the US and countries around the world have adopted RPS goals. Unfortunately, relatively high cost, low efficiency and intermittency challenges preclude the possibility of a completely renewable power system in the near future. As a result, nuclear energy is receiving renewed attention because of low greenhouse gas and criteria pollutant emissions.

Recently, a technology that connects these related developments has been prominently promoted – the plug-in hybrid electric vehicle (PHEV). The PHEV concept provides consumers a vehicle option that can be conveniently recharged and operate as a pure zero emissions vehicle (ZEV) for short trips and as a hybrid vehicle for longer trips. This outstanding concept could enable a more significant use of renewable power, nuclear power, and other domestic resources to meet transportation energy demands in many countries. While this development is significant, it lacks the potential for complete sustainability because of the continued use of limited fossil resources and the emission of greenhouse gases and criteria pollutants whenever operated in hybrid mode.

Table 1
Solid oxide fuel cell attributes [11].

Attribute	Performance
High fuel-to-electricity conversion efficiency	Demonstrated – 47% (simple cycle) Achievable – 55% (simple cycle) Hybrid – 70% CCHP – 80%
Superior environmental performance	No nitrogen oxides (NO_x) Lower greenhouse gas (CO_2) Sequestration capable Quiet, fewer moving parts
Combined cooling/heating and power	High quality exhaust for heating/cooling Industrial heat use ready Co-production of hydrogen/electricity Compatible with gas turbine (hybrid), steam turbine, renewable, and other heat engines
Fuel flexibility	Low purity H_2 and H_2/CO mixtures Liquefied natural gas Pipeline natural gas Gasoline, diesel, fuel oil, military fuels Coal synthesis gas Renewable fuels: digester gas, landfill gas, biomass synthesis gas
Size and siting flexibility	Modular permitting wide range of system sizes Rapid siting due to low emissions
Application flexibility	Distributed power Central power Transportable power

2. Potential roles of fuel cells and hydrogen

2.1. Stationary power

High temperature fuel cell technology, such as molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) are most applicable to stationary power applications. Relatively high temperature operation (650–1000 °C) and oxidizing ion conduction produces fuel flexibility, ease of integration with fuel processing equipment or bottoming cycles such as gas or steam turbine cycles, as well as production of high quality heat for co-generation. When integrated with a gas turbine engine the technology is typically called hybrid fuel cell-gas turbine technology. These types of hybrid systems offer unprecedented efficiency and emissions performance. A list of solid oxide fuel cell attributes, which are representative of all high temperature fuel cells, is presented in Table 1.

The features of MCFC and SOFC systems could make them the preferred electric generation technology of the future. Three applications are particularly attractive; (1) using natural gas in a combined cooling/heating and power distributed generation application, (2) using coal synthesis gas in large integrated gasification fuel cell plants, and (3) operating on renewable fuels such as biogas. SOFC are attractive for CCHP (Fig. 1) because of their high quality exhaust heat. SOFC and MCFC are also fuel flexible and efficient at small scale, making it possible to capture waste heat without compromising electrical conversion efficiency compared to large central power plants.

On a larger scale, integrated gasification SOFC systems such as that illustrated in Fig. 2 can be operated on coal. This is particularly attractive for the United States since the US has a large amount of coal. Generating efficient, pollutant free energy from coal is highly desirable, especially for energy and national security. What makes SOFC systems even more attractive is that they could operate off of biogas. Green waste can be anaerobically digested into digester gas or gasified into a hydrogen- and carbon monoxide-rich stream. The digester gas or biomass synthesis gas can then be converted effectively to electricity and high quality heat in SOFC combined heat and power (CHP) plants. SOFC systems can provide benefits to electrical power generation no matter what type of hydrocarbon fuel we use in the future; whether it (1) continues to be natural gas and coal, or (2) becomes a renewable-fuel such as biomass or waste.

2.2. Transportation

Hydrogen fuel cell vehicles, like pure electric vehicles, offer the advantage of zero pollutant emissions at the vehicle point of use. While hydrogen storage technologies have been significantly advanced to demonstrate reasonable vehicle range [25], the physical properties of hydrogen suggest that it will never possess the high energy density and ease of storage that are required for an ideal transportation fuel. Furthermore, current fuel

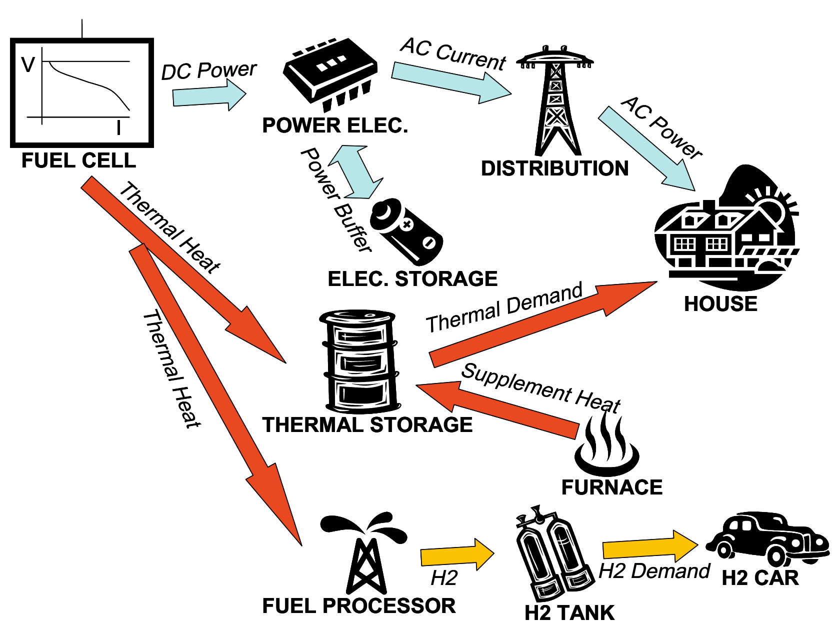

Fig. 1. Concept of distributed generation: capturing the waste heat, supporting the utility grid, and locally generating hydrogen [29].

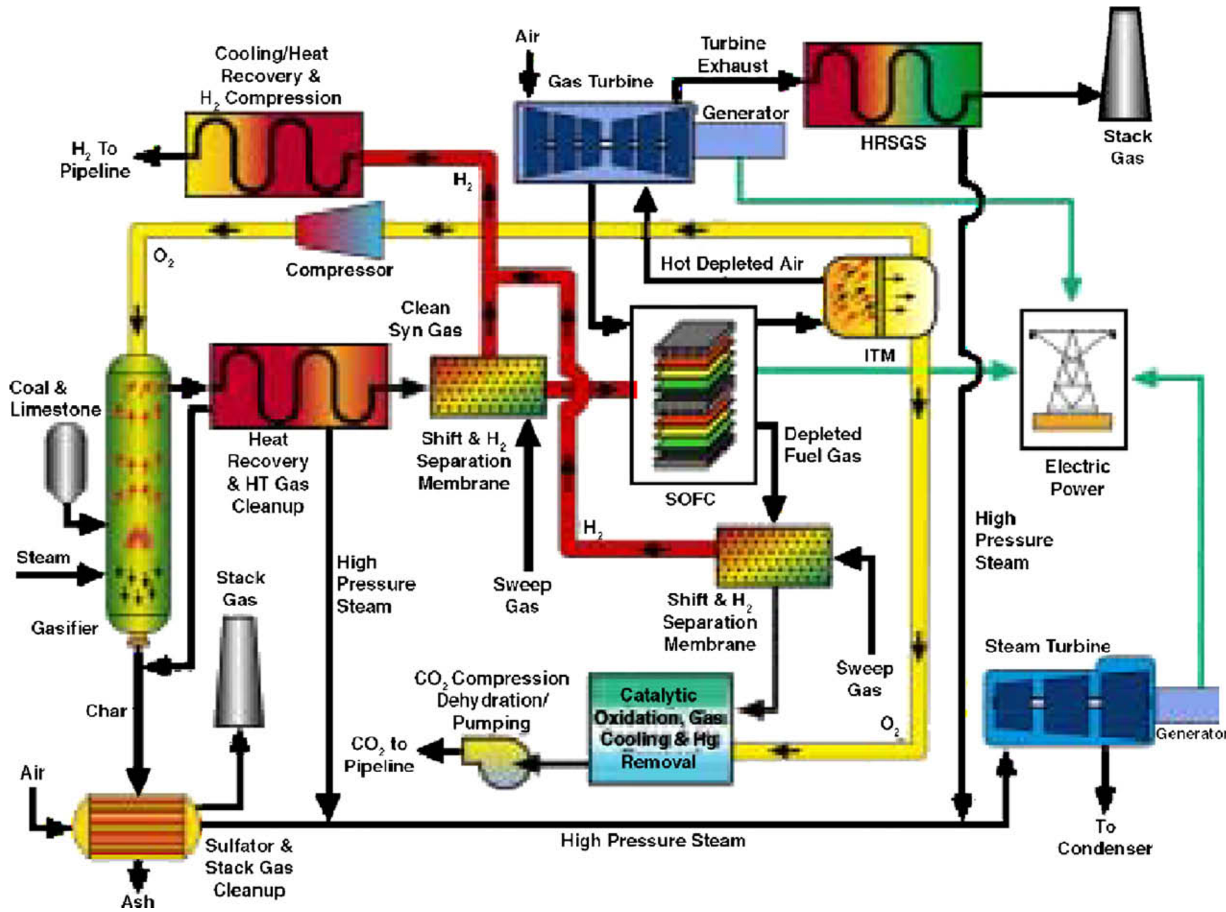

Fig. 2. Simplified schematic of a FutureGen central power plant [11].

cell vehicles are very expensive and demonstrate sub-par reliability and service lifetime.

Even if the numerous challenges facing fuel cell vehicles can be solved (e.g., cost, hydrogen storage, fuel cell reliability), the energy and emissions penalties associated with hydrogen production, transport and dispensing ("well-to-tank" path) remain problematic [26]. Hydrogen is currently produced economically from natural gas reformation, which obviously fails to solve greenhouse gas emissions, fossil fuel use, and sustainability challenges.

Hydrogen can be produced through electrolysis of water using renewable electricity. This strategy has very low emissions and is much more sustainable, but, it is very high cost and fraught with inefficiency. The cumulative inefficiencies associated with producing hydrogen from water via electrolysis suggest that any future renewable electricity could offset more pollution, carbon emissions, and fossil fuel use by direct use as electricity (instead of inefficiently generating hydrogen for vehicle fuel) [21]. Without major, unforeseen hydrogen generation and storage breakthroughs, hydrogen vehicles are at best a mitigation strategy, and at worst, a distraction from seeking more comprehensive solutions.

Pure battery electric vehicles (BEV) competed directly with combustion engine vehicles at the dawn of the automobile age and electric cars have been developed and investigated repeatedly ever since. The most intensive research occurred in the 1990s in response to California's zero emission vehicle (ZEV) mandate. However, despite zero tailpipe emissions, a broad array of energy sources, and virtually no dependence on oil, the public has never accepted electric vehicles because they fail to address the first two issues of the transportation challenge; battery electric cars do not offer the transportation performance expected by most drivers because BEVs charge too slowly and have a limited driving range which decreases freedom of mobility [27]. If these drawbacks are someday overcome through secondary battery technological advancements, BEVs may provide a near-perfect personal transportation solution. However, huge investments in battery technology advancement, while producing significantly better performance like that of current lithium–ion technology, have not been able to produce technology sufficient to meet consumer demands for charging time and range. These investments and corresponding technology improvement trajectory (100 mile range in the 1990s, 150 mile range in the future [28]) suggest that the likelihood of producing cost effective battery technology that meets vehicle consumer demands is low.

These issues direct consideration of fuel cells in transportation to the more limited role of meeting long-distance driving demands of future plug-in hybrid fuel cell vehicles (PHFCV). PHFCVs could use domestic, renewable, stationary fuel cell generated, carbon-sequestered, nuclear and other more sustainable and low-to-zero greenhouse gas and pollutant emissions electric power to meet most future transportation energy demands. The fuel cell would be used only for long-distance trips, reducing the size and cost of the fuel cell engine and the hydrogen storage components and reducing the demand for costly hydrogen that would otherwise have been required for non-plug-in fuel cell vehicles.

3. Related NFCRC projects

The National Fuel Cell Research Center (NFCRC) is conducting research in a number of projects that are directly related to the future role of fuel cells and hydrogen in a more sustainable and renewable energy future. A few of these projects are summarized in this section of the paper.

NFCRC has been working to advance understanding of high efficiency, zero emissions coal-based power plants that use hybrid fuel cell-gas turbine technology. An example of one such plant that has been conceptualized and analyzed by NFCRC is presented in Fig. 3. Note that such a future technology can provide a pure CO2 stream for sequestration, and co-produce hydrogen and electricity (from an SOFC, gas turbine and steam turbine) with a mixed overall efficiency of 65%. These systems would also have nearly zero emissions of criteria pollutants making them a very attractive option for future use of coal in a more sustainable manner.

NFCRC has been evaluating systems based on the generation and utilization of hydrogen at a single residence. A prototype Hydrogenics (formerly Stuart Energy Systems) "HomeFueler" has been installed, commissioned and put into service to fuel Toyota fuel cell hybrid vehicles. Such systems use electrical power that would ideally be provided by renewable resources such as solar and wind, to generate, compress, store and dispense hydrogen for use in passenger vehicles. A Proton Energy Systems electrolyzer system has been operated with a photovoltaic power source and installed in parallel with a Relion PEM fuel cell system as a reversible hydrogen fuel cell system as shown in Fig. 4. These systems allow storage of renewable energy when production exceeds demand and electrical power generation when demand exceeds production and can provide hydrogen for other uses.

Dynamic performance calculations for such systems have shown that a 4.2 kW reversible fuel cell system together with a 5 kW photovoltaic roof and some battery storage can meet all the dynamic power demands of a single residence (as shown in Fig. 5) and produce additional hydrogen (1.53 kg in one week – sufficient for an ~18 mile weekday commute). While such production of electricity and transportation fuel from photovoltaic power is attractive for sustainability, the costs of such systems is currently and is expected to remain very high in comparison to more centralized systems (e.g., neighborhood level systems containing similar design components).

NFCRC has also been modeling Energy Station systems based on the utilization of high temperature fuel cells for the co-production of electrical energy, high quality heat and hydrogen fuel. Molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) can be operated in such a way that excess hydrogen can be generated from hydrocarbon feedstocks in the fuel cell stacks themselves. An example of such a concept is shown pictorially and schematically in Fig. 6. Optimizing for electrical power during peak daytime periods and optimizing for hydrogen generation during off-peak nighttime periods would be economically attractive as it would level the base load on the fuel cell system.

NFCRC has developed thermodynamic and dynamic system models to evaluate how such systems would perform under these different operating modes. NFCRC has found that internally reforming SOFC and MCFC systems produce the most hydrogen, can operate most efficiently, and with ultra-low emissions may be the most effective means of introducing initial hydrogen infrastructure. Fig. 7 shows that overall first law efficiency can approach 80% for such systems with significant hydrogen production. Such highly efficient local production averts the efficiency and emissions penalties associated with hydrogen transport.

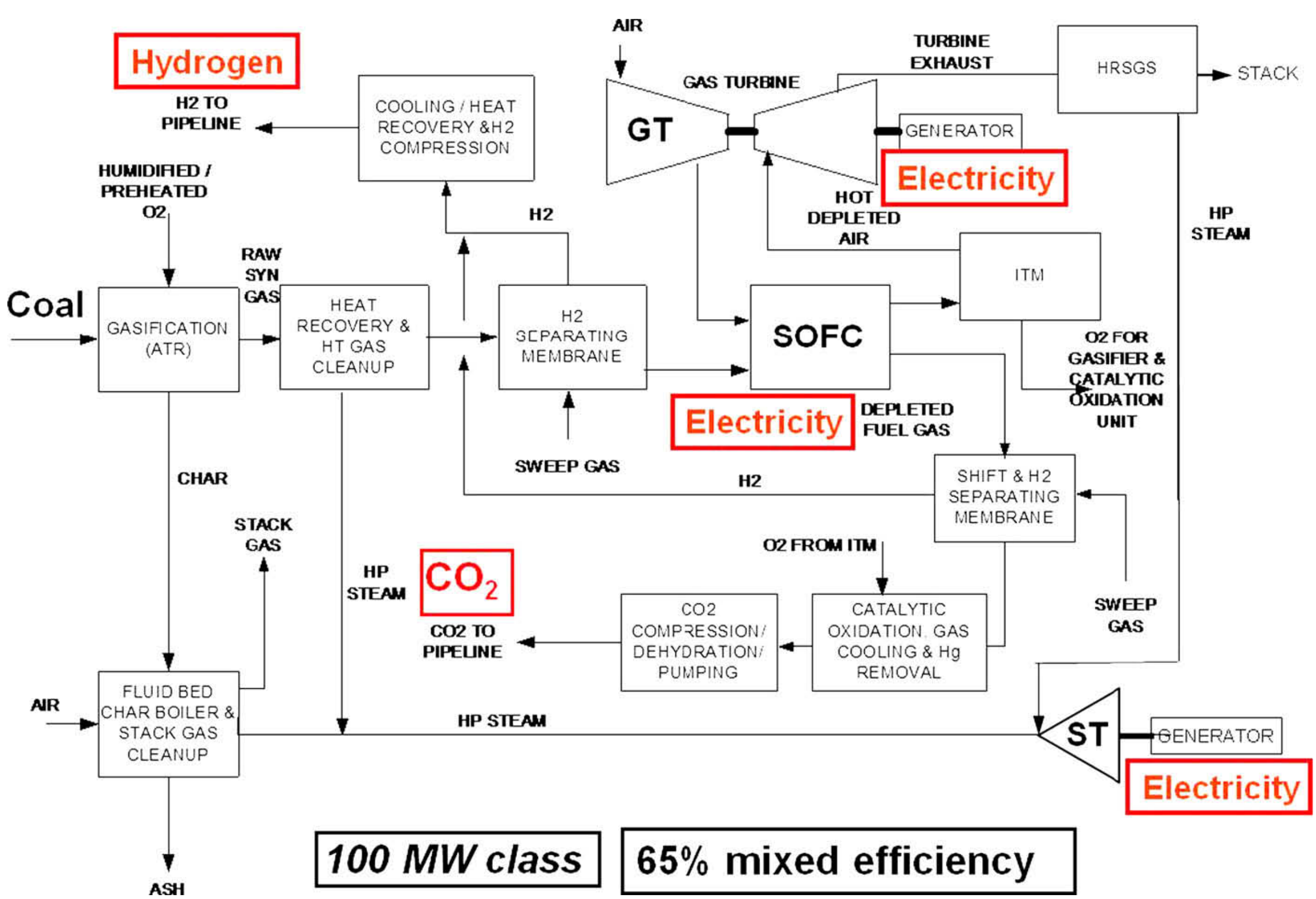

Fig. 3. Example future coal-based central power plant using hybrid fuel cell-gas turbine technology.

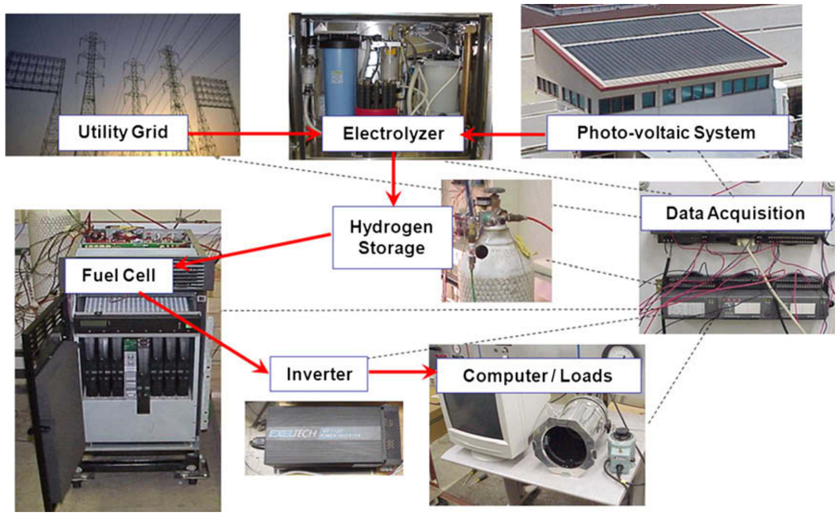

Fig. 4. Renewable residential scale fuel cell system with hydrogen co-production.

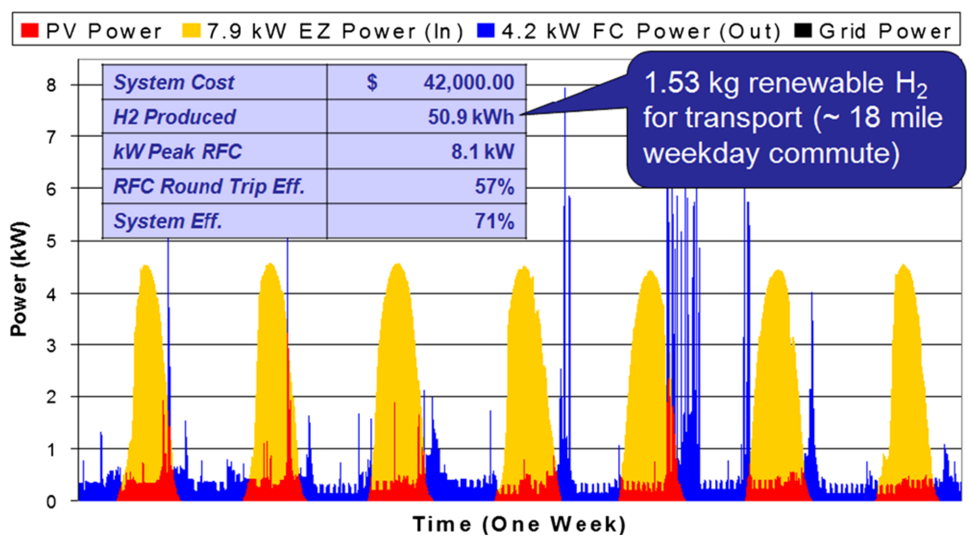

Fig. 5. Dynamic power demand and supply for a renewable residential scale fuel cell-electrolyzer system.

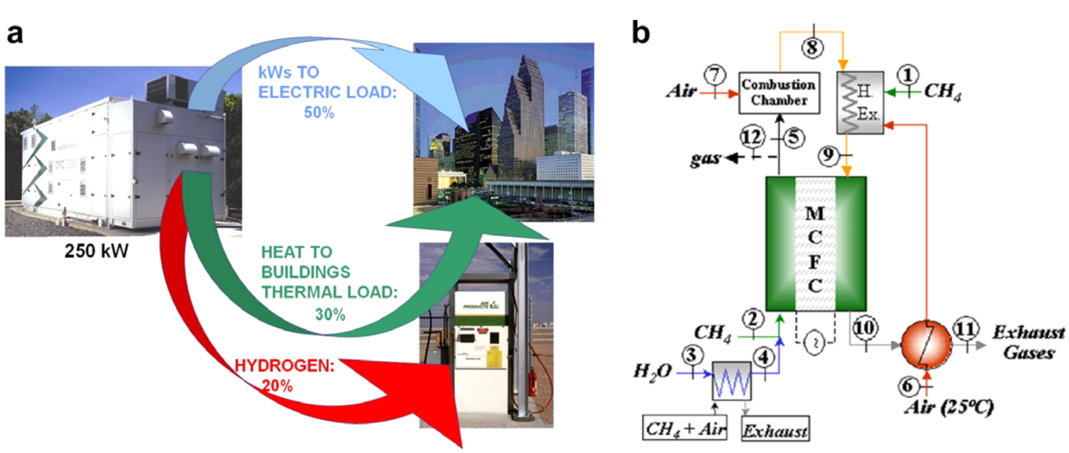

Fig. 6. Picture (a) and schematic (b) of an internal-reforming molten carbonate fuel cell electricity and hydrogen co-production system.

NFCRC is also testing fuel cell vehicles from Toyota and General Motors and developing, installing and managing hydrogen fueling capabilities throughout Orange County of California with Air Products and Chemicals, Inc. (see Fig. 8). The fuel cell vehicles from

Toyota and GM are proving the outstanding performance (e.g., acceleration), mileage, range and rapid fueling capabilities that fuel cell vehicles can achieve.

NFCRC is pioneering the investigation of battery electric vehicles in shared use, mass transit integrated transport systems through its Zero Emission Vehicle Network Enabled Transport (ZEV-NET) program. The ZEV-NET program has included the introduction of a significant electric vehicle charging infrastructure, a web-based reservations system, a vehicle GPS tracking system for each electric vehicle, and an underlying database for gathering information and controlling vehicle availability and reservations. Together with Toyota, we have been able to test full-featured electric vehicles based upon the Rav-4 EV and prototype electric vehicles, such as the "e.com," in the ZEV-NET program. More information on ZEV-NET can be found at http://www.zevnet.org/.

Finally, NFCRC is working with funding from the California Air Resources Board to investigate plug-in hybrid electric vehicles, the required test protocols and the potential impacts of widespread

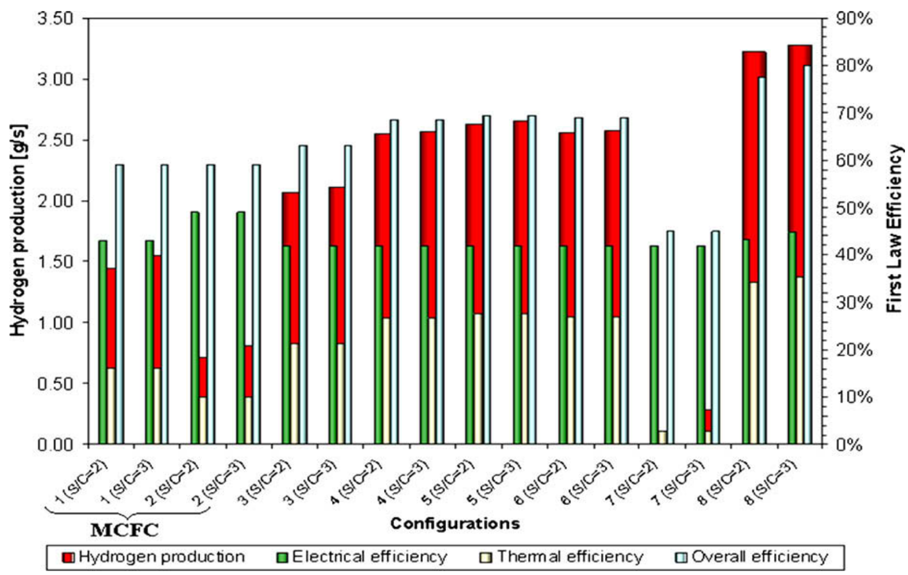

Fig. 7. Energy performance analyses of various high temperature fuel cell electricity and hydrogen co-production configurations.

Fig. 8. (a) Fuel cell vehicles under test at the NFCRC and (b) one of the NFCRC H_2 fueling stations.

PHEV use on the electric utility grid and air quality. NFCRC partners in the effort include Toyota Motors, Horiba Instruments, and the South Coast Air Quality Management District. Toyota is providing several of their prototype PHEVs (see Fig. 9) for use in the investigation.

4. Convergence of technologies

Recent work at the NFCRC and several other research groups e.g., [23–25] consistently points to the need to increasingly use electricity in the transport sector as the best way to make transportation energy conversion more sustainable. At the same time analyses of future power plant technologies, conducted by the NFCRC and others, consistently points to the use of hybrid fuel cell-gas turbine and CCHP systems together with new renewable and nuclear power to more sustainably meet future power demands. In addition to making power and transport energy more sustainable, each of these paradigms also addresses geopolitical concerns associated with energy imports.

These developments suggest a convergence of stationary and transportation energy technologies that involves the use of fuel cells and hydrogen to enable greater sustainability. Stationary fuel cell systems with CCHP can be integrated into efficient industrial processes, commercial buildings and neighborhoods to immediately meet electricity demands. These systems will make better use of limited fossil fuels and will increasingly use renewable (e.g., landfill, digester) and waste fuel streams. These systems will eventually evolve fuel cell technology to the point of serious consideration in larger central power plants that could further more sustainable and environmentally sensitive use of coal. These "dispatchable" stationary fuel cell systems will well compliment the increasing adoption of intermittent new renewable power generation and long-term adoption of more sustainable nuclear power plants. All of these technologies will together be required to produce electricity for both stationary power demands and for the increasingly large demand from plug-in hybrid electric vehicles.

While fuel cell engines and delivered hydrogen remain too expensive and hydrogen infrastructure remains un-available in the short-term, PHEV technology should be increasingly adopted in transportation applications. Battery electric based energy storage concepts for transport can most efficiently use the new renewable, nuclear and fuel cell power that is introduced. In addition to making the grid more renewable and sustainable, using the electric utility grid to meet transportation energy demands would will increase grid efficiency and reliability, introduce new clean technologies, and smooth the load curves (reducing the peak to base-load demand ratio). A graphical representation of the convergence of electric power and transportation technologies is presented in Fig. 10.

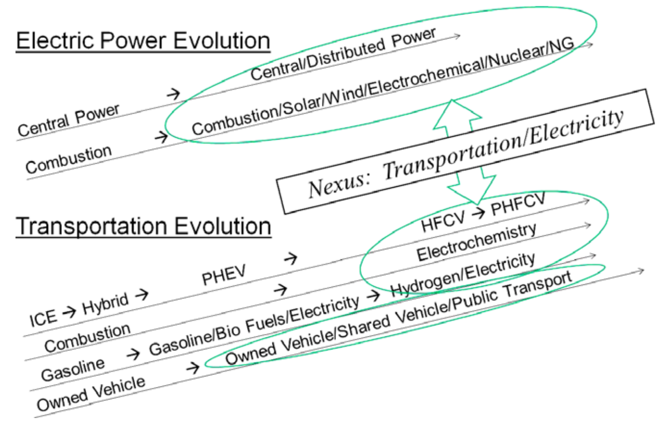

Fig. 10. Convergence of electric power and transportation technologies involving fuel cells and hydrogen.

Transportation fuel cell engines and hydrogen use as an energy carrier can then be developed upon the backbone of technologies that comprise the nexus of transportation and electricity shown in Fig. 10. Only after direct use of electricity to meet transportation demands becomes ubiquitous should one consider introducing fuel cell vehicles and hydrogen infrastructure into the transportation energy paradigm. But eventually petroleum-based distillate fuels will become too scarce and costly to use for meeting the longer-trip demands of vehicles. Fuel cell engines can then be built upon the hybrid drive train technology used in PHEVs to meet long-trip transportation demands. It is likely that fuel cell size required by such PHFCVs will be relatively small, that hydrogen storage will be improved, and that hydrogen infrastructure will be increasingly available to enable such a technology shift. And the very same stationary fuel cell, renewable and nuclear power generating technologies introduced initially to meet power demands more sustainably can also be used to produce the hydrogen required for this transition.

Fig. 9. Toyota PHEV under investigation at NFCRC.

5. Conclusions

A convergence concept is presented in which fuel cells and hydrogen can be evolved to more sustainably meet power and transportation energy demands in the future. Stationary fuel cell systems can provide continuous power with extremely low (or zero) criteria pollutant and greenhouse gas emissions from a variety of renewable and fossil fuels that well compliments the relative intermittency of many forms of renewable power. The sustainability of energy conversion is aided by the highly efficient use of limited fossil fuel reserves, of renewable fuels such as biogas, landfill and digester gas, and of waste fuel streams that can be accomplished using a fuel cell system. These systems can also, eventually, efficiently co-produce hydrogen to meet energy carrier demands.

Use of hydrogen as an energy carrier can enable transportable power with zero pollutant and greenhouse gas emissions at the point of use. In addition, hydrogen can be efficiently produced with very low emissions from a variety of renewable and more sustainable primary energy sources such as wind, solar, and nuclear power (by water electrolysis or splitting), from biogases and industrial waste streams, as well as from domestic fossil fuels such as natural gas and coal.

While there are many significant technical hurdles to overcome before fuel cell technology can become widely available and while significant investments will be required to enable the widespread use of hydrogen as an energy carrier, plug-in hybrid electric vehicles should be widely adopted. PHEV technology can efficiently meet transportation energy demands with lower emissions and lower fossil fuel use while supporting the introduction of new renewable and clean power generation. Then, fuel cell engines and hydrogen infrastructure can be built upon the PHEV and new power generation framework to meet long-trip transportation energy demands. A set of projects being conducted at the National Fuel Cell Research Center is beginning to prove the technical effectiveness of the convergence concept and to address the technical and economic hurdles for future widespread use of fuel cells and hydrogen (Fig. 8).

Acknowledgements

The author gratefully acknowledges the financial support of the US Department of Energy, and US DoD Engineer Research and Development Center, which have provided partial support for some of the work presented herein. The author also acknowledges the significant contributions of Mr. James D. Maclay, Dr. Fabian Mueller, Dr. Tim Brown, Dr. Ashok Rao and Professor Scott Samuelsen to the NFCRC projects summarized in this paper.

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