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Understanding the design and economics of distributed tri-generation systems for home and neighborhood refueling—Part I: Single family residence case studies

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ABSTRACT

The potential benefits of hydrogen as a transportation fuel will not be achieved until hydrogen vehicles capture a substantial market share. However, although hydrogen fuel cell vehicle (FCV) technology has been making rapid progress, the lack of a hydrogen infrastructure remains a major barrier for FCV adoption and commercialization. The high cost of building an extensive hydrogen station network and the foreseeable low utilization in the near term discourages private investment. Based on the past experience of fuel infrastructure development for motor vehicles, innovative, distributed, small-volume hydrogen refueling methods may be required to refuel FCVs in the near term. Among small-volume refueling methods, home and neighborhood tri-generation systems (systems that produce electricity and heat for buildings, as well as hydrogen for vehicles) stand out because the technology is available and has potential to alleviate consumer's fuel availability concerns. In addition, it has features attractive to consumers such as convenience and security to refuel at home or in their neighborhood.

The objective of this paper is to provide analytical tools for various stakeholders such as policy makers, manufacturers and consumers, to evaluate the design and the technical, economic, and environmental performances of tri-generation systems for home and neighborhood refueling. An interdisciplinary framework and an engineering/economic model is developed and applied to assess home tri-generation systems for single family residences (case studies on neighborhood systems will be provided in a later paper). Major tasks include modeling yearly system operation, exploring the optimal size of a system, estimating the cost of electricity, heat and hydrogen, and system CO_2 emissions, and comparing the results to alternatives. Sensitivity analysis is conducted, and the potential impacts of uncertainties in energy prices, capital cost reduction (or increase), government incentives and environmental cost are evaluated. Policy implications of the modeling results are also explored.

1. Introduction

Although hydrogen fuel cell vehicle (FCV) technology has been making rapid progress [1,2], the lack of a hydrogen infrastructure remains a major barrier for FCV adoption and commercialization. Wide availability of hydrogen is critical to the public support and commercial success of hydrogen as a transportation fuel; yet, the high cost of building an extensive hydrogen station network and the foreseeable low utilization in the near term discourages private investment and slows infrastructure deployment [3].

Various infrastructure build-out strategies have been proposed to initiate FCV adoption. One approach is focusing early FCV deployment (both vehicles and stations) in selected, concentrated geographic regions such as Los Angeles and New York [3,4]. An initial sparse network of public hydrogen stations is located near early adopters in a limited number of regional "clusters". Although this strategy can improve consumer accessibility to fuel, high cost and low utilization of hydrogen refueling stations are still issues.

In this paper we explore a different paradigm: use of small-scale home and neighborhood refueling as a path toward commercializing FCVs. In particular, we assess "tri-generation" systems that produce electricity and heat for buildings, as well as hydrogen for vehicles. Based on the past experience of fuel infrastructure development for motor vehicles, innovative, distributed, small-volume hydrogen refueling methods may be required to refuel FCVs at least in the near term [5]. Among small-volume refueling methods home and neighborhood level tri-generation systems stand out because the technology is available and has potential to alleviate consumer's fuel availability concerns, and has other features attractive to consumers.

Home and neighborhood refueling both have the potential to offer early wide availability of hydrogen as a transportation fuel with less investment than a dedicated hydrogen station network. The economics of small-volume hydrogen refueling systems can be

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Table 1
List of FC tri-generation/cogeneration demonstration projects.

Project	Dates	Partners	Project description
Fountain Valley Station Orange county Sanitation District, CA [11]	Operation begins in June 2010	Air Products and Chemicals, Inc., DOE California Hydrogen Infrastructure Program	Designed to co-produce power, hydrogen and heat; 100 kg day^{-1} hydrogen capacity, and will be expanded; over 200 kW electricity supply; 35 MPa and 70 MPa fueling capability (H_2 purity: >99.99%, CO: <0.2 ppm, CO_2: <2 ppm).
Hawaii Hydrogen Power Park [12,13]	Construction 2003 to present	State of Hawaii, Hawaii Volcanoes National Park, Kilauea Military Camp (DoD), Hawaii Ctr for Adv. Transp. Technology, etc.	The system provides power and hydrogen for hydrogen-fueled vehicles; hydrogen is designed to be produced by sources including hydro, wind, geothermal and solar, or various sources of biomass, or reformation of biofuels (H_2 purity: >99.95%); designed to support the operations of the National Park Service hydrogen plug-in hybrid electric shuttle buses for 24 months through to January 2013.
The Toronto Hydrogen Energy Station, Toronto, Canada [7,14]	Installation begins in August 2003	Hydrogenics, Canadian Transportation Fuel Cell Alliance, City of Toronto, h2ea, Purolator	The world's second energy station; with on-site H_2 production, storage and dispensing capabilities; can produce power; can produce 20 kg day^{-1} of H_2; designed to fuel a commercial work vehicle and a fuel cell hybrid bus (H_2 purity: >99.99%, CO: <1 ppm, CO_2: <1 ppm).
Latham, New York H_2 Home Energy Station [15,16]	Opened November 2004	Honda R&D Americas, Plug Power	Designed to power a home, provide hot water and generate hydrogen fuel for refueling FCVs (H_2 purity: >99.95%).
Torrance, California Home Energy Station [7,16]	Opened October 2003	Honda R&D	Designed to power a home, provide hot water and generate hydrogen fuel for refueling FCVs. American Honda uses this fueling station to fuel their internal four car fleet (H_2 purity: >99.99%).
The Las Vegas Hydrogen Energy Station [7]	Opened August 2002	Air Products, Plug Power, City of Las Vegas, DOE	The world's first tri-generation energy station with a 50 kW PEM (proton exchange membrane) FC sub-system; initially used onsite NG reforming with liquid H_2 backup, in 2004 added fueling station supplied by 50 kW PEM electrolyzer power by solar cells; fuels two Honda FCVs and provides electricity to the Las Vegas grid.

Note: There is tri-generation interest in Europe and Asia as well; however; because of page limit, we did not provide that information in Table 1.

improved by co-producing valuable products: electricity and heat [6–8]. In addition, home and neighborhood refueling both have features attractive to consumers such as the security and convenience of refueling at home or within the consumers' neighborhood [9,10].

A number of tri-generation or cogeneration system demonstration projects are underway. Table 1 provides a list and description of these projects. Current technologies for home and neighborhood refueling focus on on-site hydrogen production using reformation of natural gas (NG), because electricity and NG are commonly available in households. Tri-generation systems are energy systems that are designed to meet the three energy needs (electricity, heat, and transportation fuel) of a typical household. Typically, these three energy needs are met by grid electricity, NG heat (some places also use electricity or oil for heating), and gasoline. A typical tri-generation system produces electricity and heat for buildings as well as hydrogen for vehicles by converting a hydrocarbon such as NG or biogas. More details on the mechanism of tri-generation systems are provided in Section 2.

Policy makers are currently assessing the status of market pull complementary policies (such as Zero Emission Vehicle regulation) and the need for additional incentives for FCVs. They are working on a California-specific infrastructure plan [17]. Home and neighborhood refueling both have the potential to be included in the plan. However, before including these refueling methods in the portfolio of infrastructure solutions, it is important to assess the feasibility of these methods and compare them with alternatives. Specific unanswered questions include [18]:

1) What is the technical, economic, and environmental performances of home and neighborhood refueling technologies?
2) What are the constraints on the practical and economic feasibilities and implementation of these technologies? How does the performance change as the constraints change?
3) How much will consumers value the multi-faceted benefits associated with home refueling? What is their willingness to pay for the service? And how does this value change the economics of a tri-generation system?
4) How and to what extent will policy impact the commercialization of the technologies?
5) Is home refueling a permanent or transitional strategy?

The objective of this paper is to provide a set of analytical tools for various stakeholders such as policy makers, manufacturers and consumers, to evaluate the design and technical, economic, and environmental performances of tri-generation systems for home and neighborhood refueling. An interdisciplinary framework and an engineering/economic model is developed and applied to assess home tri-generation systems for single family residences (case studies on neighborhood systems will be provided in a later paper). Major tasks include modeling yearly system operation, identifying the optimal size of a system, estimating the cost of electricity, heat and hydrogen, and system CO_2 emissions and comparing the results to alternatives. Policy implications of the modeling results are also explored.

2. Tri-generation system description

A typical tri-generation system is shown in Fig. 1. A fuel reformer converts NG to a mixture of hydrogen and other gases including CO and CO_2. A water-gas shift processor converts most of the CO to hydrogen and CO_2. A purifier separates hydrogen from other impurities. Pure hydrogen can be used by a FC sub-system to generate electricity and heat, and can be compressed and used to refuel a car. Certain amounts of hydrogen can also be compressed and stored depending on the system's operational strategy and configuration.

We considered a number of potential strategies that define how tri-generation systems could operate, described below. Other strategies are possible as well.

- *Stand alone vs. grid-connected*. Stand alone system is not connected with the grid. All energy needs are satisfied with the system and NG supply. For a grid-connected system, the system is connected with the grid and able to buy or sell electricity to and from the grid when it is more economical to do so.
- *Heat vs. electricity load following*. For heat load following strategy, the system operates to follow the heat load. For electricity load following, the system operates to follow the electricity load.
- *Fixed vs. flexible refueling pattern*. For fixed refueling pattern, the system requires customers to refuel at certain time of day. The hydrogen storage unit can be eliminated or very small under this strategy. For flexible refueling pattern, the system allows cus-

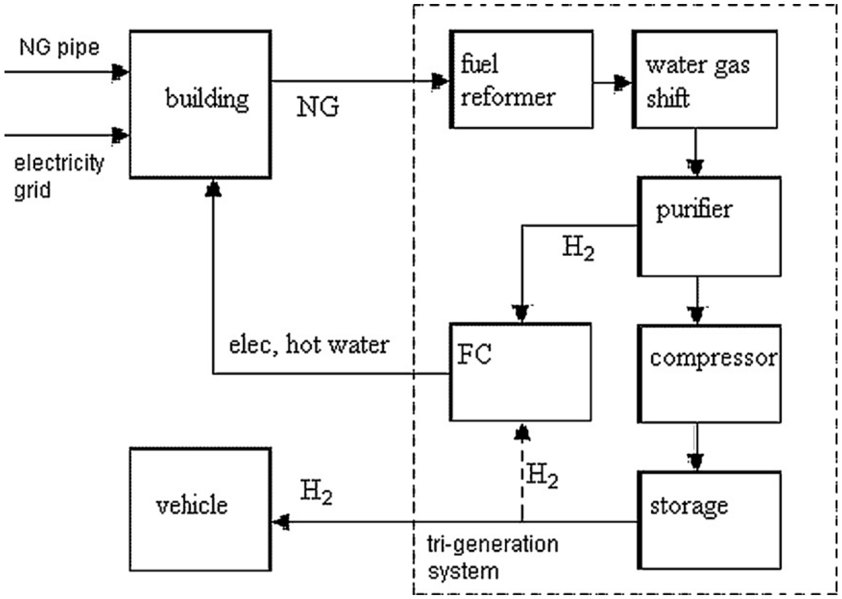

Fig. 1. The schematic representation of a typical tri-generation system.

tomers to refuel whenever they want within a few minutes. A certain amount of hydrogen storage is needed.

Operational strategies can significantly affect the optimal system size and the economics of tri-generation systems, given energy consumption data and energy prices. In this study, a grid-connected system with an electricity load following strategy is used as a base case. This provides ample heat recovery for hot water loads from typical residential demand profiles, and avoids the high cost of providing bigger system capacity to meet peak power demands with a stand-alone system. The case studies evaluate both fixed and flexible refueling patterns as well.

3. Methods and data

3.1. *An interdisciplinary analytic framework*

An interdisciplinary framework is developed to systematically analyze tri-generation systems. This framework can also be applied to other energy systems such as electrolyzer stations powered by grid or renewable electricity. The framework integrates factors from fields including thermodynamics, chemical engineering, economics, and consumer behavior research, and is illustrated in Fig. 2. The framework consists of two main stages: first, the engineering modeling of hydrogen production and electricity and heat generation; second, the engineering economic analysis of installing and operating the systems. In the first stage, physical property data of energy systems and relevant governing equations are incorporated into the engineering modeling process. In the second stage, engineering economic analyses are conducted on the basis of the engineering performance and cost data; consumer preference and environmental cost information is integrated into the modeling process as well. More details on consumer preference and environmental cost are provided in Section 3.2. The last arrow highlights the outputs of the analyses.

A model developed under this framework allows us to compute the levelized costs of energy products, which can be in the form of electricity, heat, or hydrogen. System emissions are another important output. The optimal sizes (the size allows a tri-generation system to meet three energy needs with minimal cost) of a system or components are also of interest to manufacturers and

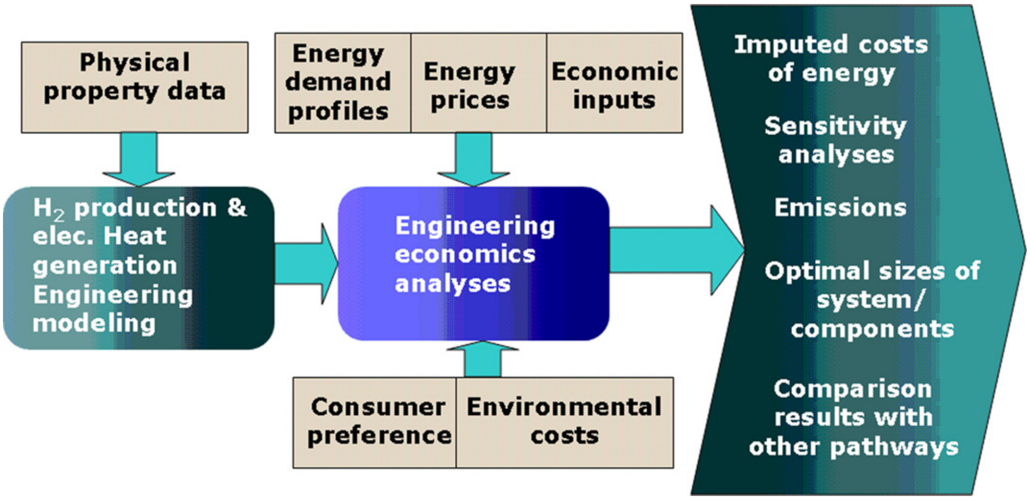

Fig. 2. Interdisciplinary framework for analyzing tri-generation systems.

Table 2
Main assumptions and data inputs.

Engineering performance data and assumptions	Components and system efficiency are based on material and energy balance modeling and experimental data.
Case study area	Northern California/Sacramento.
Energy consumption data and assumptions	Hourly energy demand profiles (electricity, heat, and transportation fuel) for the entire year are used. We employ data for a representative single family residence in northern California Sacramento area, provided by California Energy Commission.
Energy price data	Historical data are used for natural gas, electricity and gasoline prices in the Sacramento area. Projected near-term hydrogen prices are from conceptual design studies by other researchers [3].
Capital cost assumptions	A competitive market for FC systems is not well developed. As a result, the current market price may not necessarily reflect the manufacturing cost. We choose to use an estimated manufacturing cost plus a markup, and installation, maintenance, and operation cost in this study. In addition, we assume that home and neighborhood tri-generation systems are designed as appliance type systems, and non-equipment costs such as site development, rent for landscape can be significantly reduced compared with current practice in installing public hydrogen refueling stations.
Other economic assumptions	We assume a real discount rate of 8% and calculate the capital recovery factor (*CRF*) based on a 10 year equipment lifetime. *CRF* = 0.146.

Table 3
Main engineering parameters.

Reformer efficiency [8]	75% (this parameter represents the combined efficiency of fuel reformer, water gas shift processor, and purifier in Fig. 1)
FC stack efficiency η_{FC} (also shown in Fig. 3) [8,20,21]	$\eta_{FC} = \{1 - \exp[-0.5(P/P_{FC,max})^{1.2}]\} \times [0.622 - 0.002(P/P_{FC,max})]$, P is the hourly average electricity demand load (kW), and $P_{FC,max}$ is the capacity of the FC sub-system (kW). (this is LHV efficiency, and the function is derived by fitting the function to the measured performance of a 50 kW PEMFC stack delivered to the US Department of Energy [8])
Compressor efficiency [22]	80%
Parasitic load efficiency, the percentage of generated electricity used for parasitic load [20]	15%
AC/DC power conversion efficiency [8]	92%
H_2 utilization in fuel cell [8]	85%
Hot water tank efficiency (NG to hot water heat) [8]	75%
Rate of heat (by product of electricity generation) captured for hot water [8]	70%

consumers. It is worth noting that model results vary with data inputs and main assumptions. Table 2 presents a summary of main data sets and assumptions in this paper. More details on data and assumptions can be found in Sections 3.2 and 3.3. Sensitivity analyses are important to evaluate the impacts of changes in assumptions that are subject to uncertainty such as system capital costs and energy prices.

3.2. The HTS (H_2 tri-generation system) model

On the basis of the framework, an engineering/economic model for hydrogen tri-generation systems (HTS model) is developed and used. The model is developed utilizing a "grey box" modeling approach, which is a strategy for investigating a complex object with certain level of knowledge or assumptions about its internal make-up, structure or parts [19]. As shown in Fig. 1, there are five major components (a fuel reformer, a water gas shift processor, a purifier, a compressor, and a FC sub-system) within a tri-generation system. Performance of individual components within the system is represented in a simplified way that allows them to be incorporated into an idealized model of the system. Each component is modeled based on thermodynamics and other relevant engineering theories, and the efficiency of each component can be calculated. The FC stack efficiency curve is shown in Fig. 3 as an example. The efficiency of the entire system is the product of the efficiencies of all five components. Table 3 presents main efficiency and other engineering parameters used in the HTS model. These parameters are key engineering inputs in later engineering/economic analyses because the engineering performance determines the amount of NG input required to meet energy needs in the households. The amount of NG is a major component of variable operation cost.

Economic analysis is another major task of the model. Main economic questions investigated in this study include:

- How much does it cost to install and operate home and neighborhood refueling systems? When does it make economic sense for the consumer to install a particular system compared to alternatives?
- How do demand profiles (for hydrogen, electricity, and heat) influence system design?
- What role can system capital cost financing arrangements (versus upfront system purchase) play in the commercialization of these technologies?
- Many economic factors such as energy price, the discount rate, and the system purchasing cost, etc., may significantly impact the results of the cost analysis. How sensitive will the results be as these inputs change? What factors determine the results of economic analyses?
- How can environmental costs be included in the analyses? How does the cost of energy produced by these systems compare to alternatives?
- Consumers' preferences, response and, ultimately, their purchasing decision are essential to the commercialization of home and neighborhood refueling systems. Before making a purchas-

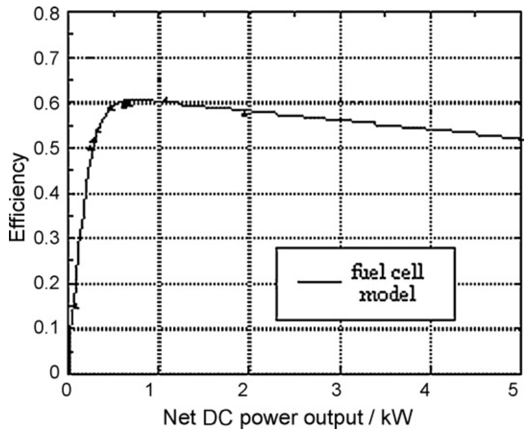

Fig. 3. Net DC power to hydrogen efficiency of the FC sub-system (modified from [8]).

ing decision, consumers evaluate the costs, and the functional, psychological, and social benefits associated with a product or service. If the price of a product or service is above his/her willingness-to-pay (WTP), a consumer will not purchase the product or service. Relevant questions on consumers' preferences include: what is consumers' WTP for the potential innovative benefits associated with home and neighborhood refueling? How can these benefits and WTP value be incorporated into the model to better understand the opportunities and barriers for the commercialization of these technologies? What is the impact of consumers' WTP on the economics of installing and operating home and neighborhood refueling systems?

With a tri-generation system there are three energy products: electricity, heat, and hydrogen, which complicates the economic analysis. One economic analysis approach is to calculate the net present value of owning and operating a tri-generation system relative to other options for supplying these three energy products (such as the conventional systems of purchasing grid electricity, NG hot water heat, and gasoline or hydrogen from a public station for transportation fuel). An economically viable tri-generation system will have a positive net present value (NPV). To compete with conventional systems, the tri-generation system should have a higher NPV than the conventional system. Another approach is to estimate the levelized cost of one energy product (electricity) while calculating the value of other products (hot water heat, and gasoline or hydrogen) based on the market price. During the life time of a tri-generation system, the same amount of electricity will be supplied as the energy profiles demanded. Levelized cost of electricity (LEC) is the constant cost of each kWh that would be incurred over the life time of a tri-generation system. The LEC can be compared to the price of grid electricity, as a metric for when the tri-generation system is competitive with the conventional systems. Levelized cost of hydrogen can also be calculated by incorporating the value of electricity and hot water heat based on the market price.

In this paper the levelized cost approach is adopted, and main equations for this approach are explained as follows. As shown in Eq. (1), all annual tri-generation system costs are quantified at the right hand side of Eq. (1).

$$C_{\mathrm{elec}} = CRF \times CC + CC_{\mathrm{o\&m}} - Cr \tag{1}$$

where C_{elec} is the annual cost of electricity ($\$\,\mathrm{y}^{-1}$); *CRF* is the capital recovery factor; *CC* stands for the present value of life cycle capital cost of a system (\$); $CC_{\mathrm{o\&m}}$ stands for annual operating and maintenance cost ($\$\,\mathrm{y}^{-1}$). *Cr* is the annual credit for heat and transportation fuel provided by the tri-generation system ($\$\,\mathrm{y}^{-1}$).

Eq. (1) can be written in greater detail as in Eq. (2).

$$C_{\mathrm{elec}} = \bar{R}_{\mathrm{elec}} \times \int P\,dt = CRF \times CC + c_{\mathrm{o\&m}} + cv_{\mathrm{o\&m}} - Cr \tag{2}$$

where $\bar{R}_{\mathrm{elec}}$ is the LEC ($\$\,\mathrm{kWh}^{-1}$); P is the hourly average electricity demand load (kW), and $\int P\,dt$ is annual electricity demand ($\mathrm{kWh\,y}^{-1}$); $c_{\mathrm{o\&m}}$ is the fixed annual operating and maintenance cost (independent of the amount of energy produced) including labor, maintenance costs, and overhead ($\$\,\mathrm{y}^{-1}$); $cv_{\mathrm{o\&m}}$ is variable annual operating and maintenance cost (which depends on the amount of energy produced) including feedstocks, water, and chemicals ($\$\,\mathrm{y}^{-1}$).

Eq. (3) can be derived based on Eq. (2).

$$\begin{aligned}\bar{R}_{\mathrm{elec}} \times \int P\,dt &= CRF \times (CC - C_{\mathrm{MTP}}) + c_{\mathrm{o\&m}} + R_{\mathrm{NG}} \times n_{\mathrm{NG}} \\ &\quad + \int R_{\mathrm{ele}}\theta_1(P)\,dt + \int R_{\mathrm{ele}}\theta_2(P)\,dt - c_{\mathrm{heat}} - c_{\mathrm{transport}} - t_{\mathrm{carbon}}\end{aligned} \tag{3}$$

$\theta_1 = P$, $P < 1/5\ P_{\mathrm{FC,max}}$ (turn down ratio of the FC sub-system is 5); $\theta_1 = 0$, otherwise.

$\theta_2 = P - P_{\mathrm{FC,\,max}}$, $P > P_{\mathrm{FC,max}}$; $\theta_2 = 0$, otherwise.

where C_{MTP} represents consumer's willingness to pay for home refueling service (\$); n_{NG} is the amount of NG consumed ($\mathrm{GJ\,y}^{-1}$); R_{NG}, is the price of NG ($\$\,\mathrm{GJ}^{-1}$); R_{elec} is the electricity price ($\$\,\mathrm{kWh}^{-1}$); c_{heat} represents the annual credit of hot water heat (based on what it would have cost to provide heat using a conventional NG based hot water system ($\$\,\mathrm{y}^{-1}$); $c_{\mathrm{transport}}$ represents the annual credit of transportation fuel (gasoline or hydrogen), based on what it would have cost to purchase gasoline or hydrogen from a public refueling station ($\$\,\mathrm{y}^{-1}$); t_{carbon} represents a carbon tax ($\$\,\mathrm{y}^{-1}$).

Eq. (3) allows the flexibility to purchase electricity from the grid when the electricity demand load is outside the FC sub-system operation range to achieve better economics. When the demand load is higher than the capacity of an FC sub-system, the FC sub-system cannot provide enough power. The FC sub-system will be operating at full capacity, and electricity demand above its capacity will be supplied by grid electricity. At very low partial load ($P < 1/5P_{\mathrm{FC,max}}$) the entire system and component efficiencies are relatively low, and purchasing power from the grid may offer better economics. In Eq. (3) the first integral $\int R_{\mathrm{ele}}\theta_1(P)\,dt$ represents purchased power from the grid when the load is lower than $1/5P_{\mathrm{FC,max}}$ (the FC sub-system is shut down when this is the case). Also, the system allows purchasing electricity from the grid when the load exceeds the capacity of the system ($P > P_{\mathrm{FC,max}}$). The second integral $\int R_{\mathrm{ele}}\theta_2(P)\,dt$ in Eq. (3) represents purchased power from the grid when the load is higher than $P_{\mathrm{FC,max}}$ and the FC sub-system is operating at its maximum capacity level. $R_{\mathrm{NG}} \times n_{\mathrm{NG}}$, $\int R_{\mathrm{ele}}\theta_1(P)\,dt$, and $\int R_{\mathrm{ele}}\theta_2(P)\,dt$ are categorized as variable annual operating and maintenance cost.

c_{heat} and $c_{\mathrm{transport}}$ are credits incorporated because of the unique features of tri-generation systems. During the lifetime of a tri-generation system, not only costs but also energy savings incurred because consumers no longer need to buy hot water heat and gasoline or alternative transportation fuels such as hydrogen. c_{heat} is the product of annual NG consumption for hot water heating and NG price. $c_{\mathrm{transport}}$ can be calculated by multiplying annual gasoline consumption with gasoline price or annual hydrogen consumption with hydrogen price from a public refueling station.

Environmental costs can be included in this study by assigning a price to the emissions. For example, a unit carbon tax from the literature can be found and assigned to the CO_2 emission reduction/increase relative to the grid electricity, NG heat, and gasoline combination, and the cost is then included in the economic analysis. The annual carbon cost, t_{carbon}, in Eq. (3) can be calculated by multiplying the unit carbon tax with the CO_2 emission reduction/increase.

Standard methods for estimating consumers' preferences and WTP for home and neighborhood refueling benefits would require either a stated preference survey or a revealed preference analysis. This is beyond the scope of this study. Alternatively, we reviewed previous research and documents on consumer preferences on home recharging for battery vehicles as well as home refueling for compressed NG vehicles to find some WTP values that is applicable in this study. These values can subsequently be incorporated into the modeling process through variable C_{WTP} in Eq. (3) [9,10,23].

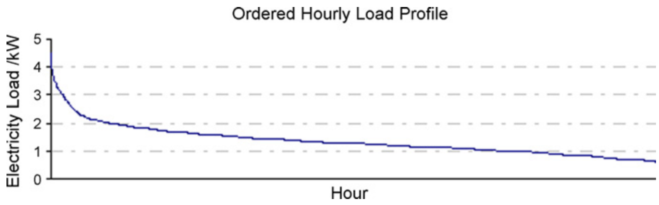

Fig. 4. Ordered annual hourly (8784 h) electricity load profile.

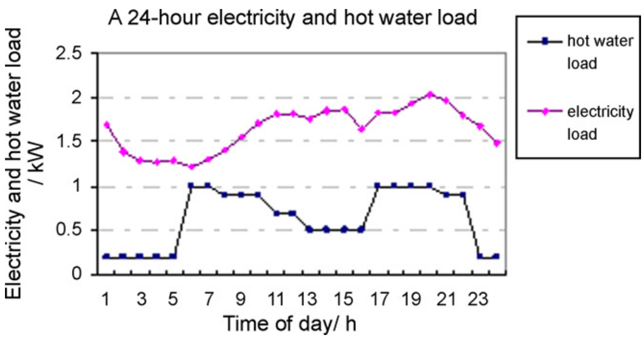

Fig. 5. Hourly hot water demand profile. (*Source*: [6,24]).

Eq. (4) is derived from Eq. (3) after simple manipulation, and is the key equation used to calculate the LEC for a particular tri-generation system configuration.

$$\bar{R}_{\text{elec}} = \frac{\begin{array}{c} CRF \times (CC - C_{\text{WTP}}) + c_{\text{o\&m}} + R_{\text{NG}} n_{\text{NG}} + \int R_{\text{ele}}\theta_1(P)\,dt \\ + \int R_{\text{ele}}\theta_2(P)\,dt - c_{\text{heat}} - c_{\text{transport}} - t_{\text{carbon}} \end{array}}{\int P\,dt} \qquad (4)$$

3.3. Energy data and other inputs

In this paper, tri-generation systems for single family residences are evaluated; these systems can be designed as an appliance-like unit (the size can be similar to a typical washing machine) installed in a garage or outside a house. Because tri-generation systems are designed to provide electricity, hot water, and transportation fuel to a residence, three sets of energy consumption data are used in this paper: the hourly electricity demand profile, hourly hot water demand profile, and transportation fuel consumption data. We employ data for a representative single family residence in northern California Sacramento area, provided by California Energy Commission. Fig. 4 shows the ordered hourly electricity load profile (also called a load duration curve); as can be seen, most electricity demand load is below 2 kW. A hot water demand profile for the whole year (8784 h) is not available, because very few agencies, if any, monitor hot water demand at this detailed level. As a result, a 24-h hot water demand profile is used to represent the whole year. Fig. 5 shows the 24-h electricity and hot water demand profiles of a particular day (January 1, 2008). Although there are weekly and seasonal variations in hot water demand, it is not expected that these variations would affect the modeling results significantly. First, hot water heating demand does not vary significantly with time and geographic locations. Second, for a typical residence the total electricity consumption is approximately double the hot water energy consumption (Table 4), and the two peaks of electricity hourly profile match that of the hot water profile. If tri-generation systems operate with an electricity load following strategy within its operation range, sufficient heat will be available for recovery for the majority of hours during a day [8]. Third, a hot water tank can be a buffer for small mismatch in electricity and hot water demand. The hot water storage currently available in residences can accommodate the variations in demand. Space heating energy is not considered in this study, because its peaks and magnitude do not match the electricity demand profile. Space heating energy demand is typically larger than electricity demand, and it normally peaks during night time when electricity load is low.

Table 4
Summary of the energy demand data (annual data based on 366 days of 2008).

Energy form	Hourly average power, kW	Annual end-use energy consumption, kWh	Demand max, kW	Demand min, kW	Demand Stdev, kW
Electricity	1.35	11,890	4.47	0.48	0.57
Hot water	0.64 (2.30 MJ h^{-1})	5,600 (20.16 GJ)	1	0.2	0.33
Hydrogen	n/a	9,090 (273 kg)	n/a	n/a	n/a
Gasoline	n/a	21,600 (601 gal)	n/a	n/a	n/a

Table 5
Some engineering/economic inputs (costs are in 2008 dollars).

Price of energy	Based on the PG & E (major utility company in Northern California) electricity and NG rate data for 2008, an electricity price of 16.8 ¢ kWh^{-1} and a residential NG rate of 3.72 ¢ kWh^{-1} (or \$10.33 GJ^{-1} and \$1.09 therm^{-1}) are used (this rate is for households with compressed NG vehicles and is appropriate for FCV owners). A gasoline price of \$3.12 gallon^{-1} is used based on EIA data for California [26].
Cost assumptions	The capital cost of a system is the sum of component costs. The FC stack needs to be replaced every 5 years.

Table 6
System component costs (in 2008 dollars).

Component	Cost
NG reformer [27]	$4{,}616 + 129P_{\text{ref,max}}$ ($P_{\text{ref,max}}$ is the capacity of the reformer in kW)
PEM fuel cell system cost [27]	Fuel cell stack: $1.1 \times \{[(454.45 - 105.4)/10 + 17.56 \times 0.6] \times P_{\text{FC,max}} \times (1 + 0.06)^5/0.6 + 428.5\}$ ($P_{\text{FC,max}}$ is the capacity of the FC stack in kW); ancillary components: $2,980.2 + 35.654 \times P_{\text{FC,max}} - 0.0422 \times P^2_{\text{FC,max}}$; inverter/controller: $542 + 169P_{\text{FC,max}}$
Storage system [27]	$284\,N_t + 192H_{\text{store}}$ (N_t – the number of tanks in the cascade filling storage system, H_{store} – hydrogen stored, kg of hydrogen).
Compressor [27]	$1{,}849.324 + 116.86P_{\text{comp}}$ (P_{comp} is the capacity of the compressor in kg h^{-1})
Dispenser [27]	$371.705 + 34.547 \times P_{\text{ref,max}}$ (for overnight, slow-fill); $474.471 + 44.098 \times P_{\text{ref,max}}$ (for flexible fast-fill)
Hot water tank [27]	0 (this is necessary for the conventional NG heating system, and the cost is canceled out)
Non-equipment (delivery and installation) [27]	5.7% of equipment capital

Note: The cost estimation is based on a 10,000 units cumulative production volume [27].

Transportation energy consumption is as large as the electricity consumption [25], assuming that a passenger vehicle in the residence is driven 15,000 miles each year, with a 25 mpg fuel economy for a gasoline vehicle and 55 miles per kg of H_2 for a FCV.

Model results vary with a number of engineering/economic inputs including efficiencies of energy conversion processes, the prices of energy, and various capital, operating and maintenance costs. Table 5 shows some of the inputs used in this paper. Table 6 presents details on component costs.

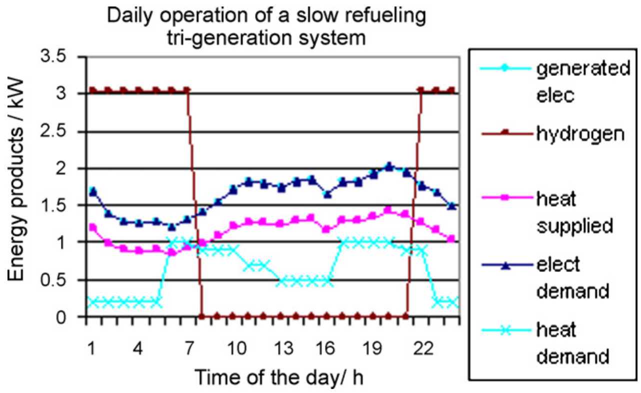

Fig. 6. Daily operation of a 2 kW electricity load following, slow refueling tri-generation system.

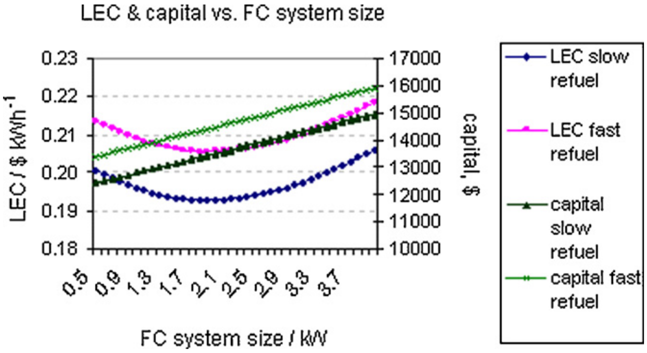

Fig. 7. LEC and capital vs. FC sub-system size for slow and fast refueling systems.

4. Case studies

4.1. The optimal size of a home system for single family residences

4.1.1. Results and discussion

The optimal size of a tri-generation system allows the system to meet three energy needs (electricity, hot water heat, and transportation fuel) with minimal cost, given energy prices. However, the fact that tri-generation systems are designed to accommodate three different energy needs makes determining the optimal size of a system complex. This is particularly true when the refueling pattern of drivers (e.g., when and how often drivers refuel) is highly variable. In this case study, the optimal size is explored using the HTS model for two system configurations. One is a grid-connected system with an electricity load following strategy and overnight, slow refueling pattern, and the other is a grid-connected system with an electricity load following strategy and flexible, fast refueling pattern. No hydrogen storage unit is configured in a slow refueling system, and it takes 10 h (10 pm to 7 am) for a vehicle to be refueled with 0.91 kg of hydrogen for a 50-mile trip. In contrast, a 4 kg hydrogen storage unit is configured in a fast refueling system to allow flexible fast refueling (with which vehicles can be refueled within several minutes) and trips longer than a regular daily commute (4 kg of hydrogen will allow a 220 mile range).

Given the assumptions in Tables 4–6 and specified hydrogen production rate based on hydrogen consumption data and assumed refueling pattern, the optimal size (the size meets three energy needs, electricity, hot water heat, and transportation fuel, with minimal cost) of a tri-generation is determined by identifying the optimal size of the FC sub-system. A "brute force" exhaustive search algorithm is used to identify the optimal size.

Fig. 6 illustrates the system operation by demonstrating the daily (24 h) energy production of a 2 kW slow refueling tri-generation system for a particular day (January 1, 2008). The system is grid-connected, so electricity demands can be met from either the FC sub-system or the grid. Because we use a turn down ratio of 1/5, the operation range of the FC sub-system is 0.4–2 kW. If the electricity demand is below 0.4 kW, the FC sub-system will be shut down because of low efficiency of the FC sub-system. If the electricity demand is higher than 2 kW, the FC sub-system will be operating at 2 kW, and electricity demand above 2 kW will be purchased from the grid. For this particular day, the electricity demand is within the 0.4–2 kW range, for all hours except for the 20th hour (8 pm). As a result, the generated electricity and electricity demand curves are the same (load following) for all hours except for the 20th hour (8 pm). The hydrogen curve shows the production of hydrogen fuel by the reformer additional to the hydrogen for electricity; the vehicle is assumed to be refueled at a constant rate during 10 pm to 7 am each day. The curves for heat generated and heat demand are presented as well.

Fig. 7 shows that when determining the optimal FC sub-system size to meet a specified power demand, there is a tradeoff between capacity factor (capital utilization) and the fraction of electricity demand that can be covered. While a larger system size could meet a greater fraction of the electricity demand, increased capital cost and lower capital utilization also result. Fig. 7 also illustrates how the LEC and capital cost change with the size of the FC sub-system. Total system capital cost is approximately linear with the system power output, because the cost of main components is linear with component capacity. This is an approximation that neglects the availability of discrete off the shelf component sizes. The FC sub-system size that results in the lowest LEC is the optimal size given the energy prices in Table 5 and the Sacramento area energy consumption data. As discussed in Section 3.2, FC sub-system sizes smaller than the optimal size have higher LEC because smaller fraction of electricity demand is covered and less heat is recovered.

As shown in Fig. 7, for the slow refueling system, the lowest LEC point (19.3 ¢ kWh^{-1}) on the curve, where the capacity of the FC sub-system is around 1.9 kW, corresponds to the optimal size. As expected the optimal size of the system is in between the maximum and minimum electricity load. For the fast refueling system, the lowest LEC is 20.6 ¢ kWh^{-1}, and the optimal size is 1.9 kW as well. It is not surprising that providing fast refueling service increases the LEC, since fast refueling requires extra costs including hydrogen storage capital cost and extra cost of a different dispenser.

The LEC shows low sensitivity to FC sub-system size around a broad minimum centered at 1.9 kW. Even if the system is not optimally sized, the impact on the electricity cost is relatively small. For example, if the system is undersized or oversized by 1 kW, the electricity cost increases by less than 2%.

4.1.2. Optimal system size sensitivity analysis

Future capital cost and energy prices are subject to uncertainty. Therefore, a sensitivity analysis is conducted for slow refueling systems to show how the optimal size changes as a result of changes in capital cost and energy prices. The results for fast refueling systems are similar, and so they are not presented here.

The optimal size is insensitive to gasoline and electricity price. A 20% increase and decrease in gasoline price significantly change the value of LEC, but have no impact on the optimal FC sub-system size. A 10% increase in electricity price only leads to a 0.1 kW increase in the optimal FC sub-system size.

The optimal size is relatively sensitive to NG price and capital cost. A 10% increase in NG price results in a 0.2 kW decrease in optimal system size, and when there is a 20% increase in NG price, the shape in Fig. 7 changes and the lowest value of LEC occurs when the system size is zero. A 10% increase in capital cost results in a 0.2 kW decrease in optimal system size. Furthermore, the higher

Table 7
System specifications for a 2 kW tri-generation system.

	Slow refuel	Fast refuel
System size (kW)	2	2
Reformer capacity (kW)	7.94	6.17
FC stack capacity (kW)	2	2
Compressor capacity (kg h^{-1})	0.24	0.19
Number of vehicles supported	1	1
H_2 production rate (kg day^{-1})	0.91	0.91
Hydrogen storage capacity (kg)	0	4

Table 8
System capital cost for a 2 kW tri-generation system.

Component	Capital Cost, $	
	Slow refuel	Fast refuel
NG reformer	5,353.5	5,188.8
PEM FC sub-system cost (FC stack, 15%; ancillary components, 66%; inverter/controller, 19%)	4,625.6	4,625.6
Compressor	1,877.2	1,620
Storage system	0	1,870.9
Dispenser	646	687.5
Hot water cogeneration	0	0
Stack (refurbish every 5 years, present value)	472.5	472.5
Non-equipment (delivery and installation)	770.3	825
Total installed capital cost	13,745.1	15,290.4

the capital cost, the more sensitive the optimal size is to capital cost. For example, a 20% reduction in capital cost leads to a 0.2 kW increase in the optimal FC sub-system size while a 20% increase in capital cost leads to a 0.3 kW decrease in the optimal FC sub-system size. The reason may be that the higher the capital cost, the larger the share of capital cost component in the LEC.

4.2. The economics of operating a 2 kW tri-generation system

4.2.1. Results and discussion

This case study evaluates a 2 kW tri-generation system in detail because it is near the 1.9 kW optimal size identified in Section 4.1. As described in Section 4.1, the system is grid-connected with an electricity load following strategy. Both the overnight, slow refueling and the fast refueling patterns are evaluated. Details on system specifications and system capital cost are presented in Tables 7 and 8, respectively. As shown in Table 8, a NG reformer is the biggest contributor to capital cost, followed by the PEM FC sub-system (including PEM FC stack, ancillary components and inverter/controller), compressor and storage system in the fast refueling case.

The LEC, annual energy cost and CO_2 emissions of a household are calculated, and these results are compared with the results of two conventional systems: the combination of grid electricity, NG hot water heat, and gasoline, and the combination of grid electricity, NG hot water heat, and hydrogen purchased from an early public station. Table 9 presents costs and credits associated with installing and operating tri-generation systems. Table 10 shows the LEC and its components.

Table 9
Costs and credits of installing and operating tri-generation systems.

	Slow refuel	Fast refuel
System capital cost, $	13,745.2	15,290.4
CRF	0.149	0.149
System capital cost (annualized), $ y^{-1}	2,127.3	2,278.3
NG input, $ y^{-1}	2,242.5	2,242.5
Grid electricity, $ y^{-1}	74.3	74.3
Heat credit, $ y^{-1}	−277.8	−277.8
Gasoline transportation fuel credit, $ y^{-1}	−1,872	−1,872
Carbon credit, $ y^{-1}	0 (base case)	0 (base case)
Willingness to pay for home refuel credit, $ y^{-1}	0 (base case)	0 (base case)
Annual electricity production, kWh y^{-1}	11,889.5	11,889.5

Table 10
The LEC and its components.

	Slow refuel	Fast refuel
System capital cost, ¢ kWh^{-1}	17.89	19.16
NG input, ¢ kWh^{-1}	18.86	18.86
Grid electricity, ¢ kWh^{-1}	0.62	0.62
Heat credit, ¢ kWh^{-1}	−2.34	−2.34
Gasoline transportation fuel credit, ¢ kWh^{-1}	−15.74	−15.74
Carbon credit, ¢ kWh^{-1}	0 (base case)	0 (base case)
Willingness to pay for home refuel credit, ¢ kWh^{-1}	0 (base case)	0 (base case)
LEC, ¢ kWh^{-1}	19.3	20.57
CA average elec. price, ¢ kWh^{-1}	16.8	16.8
Annual electricity cost with tri-generation system, $ y^{-1}	2,294.3	2,445.3
Annual cost for grid electricity, $ y^{-1}	1,997.4	1,997.4

As can be seen, capital cost, NG cost and gasoline credit are major components of LEC. The economics of installing and operating a home tri-generation system is expected to be sensitive to these three cost components.

For a slow refueling system, the LEC is about 19.3 ¢ kWh^{-1} with a capital cost of $13,745.2. The LEC is 2.5 ¢ kWh^{-1} higher than the 16.8 ¢ kWh^{-1} CA electricity price. The annual electricity cost from a tri-generation system is $ 2294, while buying electricity from the grid is $1997. There is a 14.9% or $297 increase in the annual electricity cost, using the tri-generation system, as compared to buying grid electricity.

For a fast refueling system, the LEC is about 20.6 ¢ kWh^{-1} with a capital cost of $15,290. The LEC is 3.8 ¢ kWh^{-1} higher than the 16.8 ¢ kWh^{-1} annual CA electricity price. The annual electricity cost from a tri-generation system is $2445. There is a 22.4% or $448 increase in the annual cost compared with purchasing electricity from the grid, and a 7.6% or $151 increase compared with the slow refueling system. In addition, there is a 20.52% or 2892 kg reduction in annual CO_2 emission using a tri-generation system for both slow and fast refueling patterns. Fig. 8 presents a comparison of CO_2 emissions in three cases.

Thus far, we have focused on estimating the LEC based on Eq. (4). If we instead, fix the electricity price, we can develop an analogous equation for the levelized hydrogen cost. This approach shows that a levelized hydrogen cost of $7.95 kg^{-1} is achieved using a slow refueling tri-generation system given an electricity price of 16.8 ¢ kWh^{-1} and a NG price of $10.33 GJ^{-1}. Assuming a

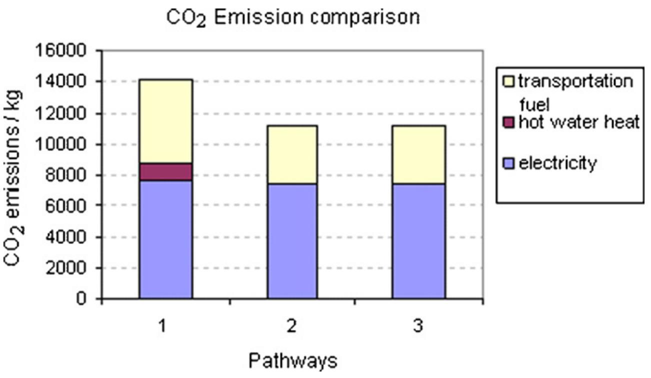

Fig. 8. CO_2 emission chart. *Note*: (1) Electricity + NG heat + gasoline; (2) slow refueling system; and (3) fast refueling system.

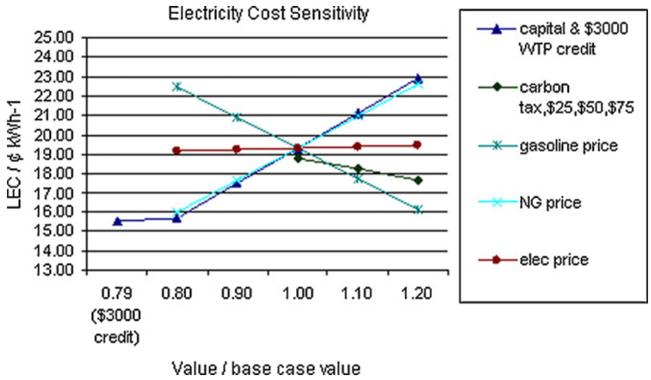

Fig. 9. Electricity cost sensitivity.

FCV has a fuel economy of 55 miles per kg of H_2 and the gasoline car fuel economy is 25 mpg, this is equivalent to a gasoline price of \$3.61 gallon^{-1} comparing fuel costs on a cents per mile basis and accounting for the higher fuel economy of a FC car compared to a gasoline car. The levelized hydrogen cost for a fast refueling system is \$8.51 kg^{-1}, giving an equivalent gasoline price of \$3.86 gallon^{-1}. In other words, holding other inputs constant, if the gasoline price exceeds \$3.61 gallon^{-1}, the tri-generation system can be competitive with the option of grid electricity, NG hot water heat and gasoline combination. This price is \$0.49 higher than the \$3.12 gallon^{-1} CA average gasoline price in 2008 and has been reached before in many California cities. Furthermore, the hydrogen cost of \$7.95 kg^{-1} is highly competitive with purchasing hydrogen from an early hydrogen station. For instance, Nicholas and Ogden [3] estimated that the levelized cost of hydrogen for three time periods in Los Angeles is:

- \$77 kg^{-1} in 2009–2011, 636 FCVs and 8–16 stations (using an average of 445 kg H_2 day^{-1});
- \$37 kg^{-1} in 2012–2014, 3442 FCVs and 16–30 stations (using an average of 2410 kg H_2 day^{-1});
- \$13 kg^{-1} in 2015–2017, 25,000 FCVs and 36–42 stations (using an average of 17,500 kg H_2 day^{-1}).

4.2.2. Sensitivity analysis

From Tables 9 and 10, we see that the major cost components determining the LEC are the system capital cost, the NG price, and the gasoline price. The HTS model allows us to evaluate the economic impact of changes in capital cost and energy prices. We also explore the impact of various credits on the economics of tri-generation systems. These credits could be policy driven for example, a feebate or tax incentive; or a credit that could reflect a consumer's willingness to pay (WTP) for the convenience of home refueling. We estimate the LEC for a case with a \$3000 WTP credit, based on the experience with natural gas home refueling. (In revealed preference estimation it was found that NG vehicle users pay around \$3000 for their home refueling systems for compressed NG vehicles [28].)

Sensitivity analysis for how the LEC varies with capital cost and energy prices is conducted by varying the capital cost and energy prices (electricity, NG and gasoline price) by −20%, −10%, 10%, and 20% compared with the base case. Sensitivity analysis results are summarized in Fig. 9 (The impact of changing the input for a fast refueling system is similar, and thus is not presented here.) In each case, it is interesting to compare the cost of electricity from the tri-generation system with the price of grid electricity (16.8 ¢ kWh^{-1}).

As shown in Fig. 9, system capital cost has a significant impact on the economics of tri-generation systems. A 10% and 20% reduction in total system capital cost results in a 9.3% (−1.7 ¢ kWh^{-1}) and 18.5% decrease (−3.5 ¢ kWh^{-1}) in LEC, and a 10% and 20% increase in total system capital cost leads to a 9.3% (1.7 ¢ kWh^{-1}) and 18.5% (3.5 ¢ kWh^{-1}) increase in LEC. A 14% reduction in system capital cost would give a LEC that is competitive with grid electricity at 16.8 ¢ kWh^{-1}. Achieving a 10–20% reduction in total system capital cost could be done by reducing the cost of key components such as the PEMFC sub-system. A 10% reduction in total system capital cost is equivalent to a 30% decrease in the FC sub-system cost, from \$2300 kW^{-1} to \$1600 kW^{-1}. A 14% reduction in total system capital cost is equivalent to a 42% decrease in the FC sub-system cost, from \$2300 kW^{-1} to \$1350 kW^{-1}. A 20% reduction in total system capital cost is equivalent to a 60% decrease in the FC sub-system cost (from \$2300 kW^{-1} to \$930 kW^{-1}). For FC sub-system costs less than about \$1350 kW^{-1}, the tri-generation system becomes competitive, holding all the other base case assumptions constant.

A \$3000 credit is equivalent to a 21% reduction in capital cost and leads to 19.5% reduction in the levelized and annual electricity cost. This level of credit would make the tri-generation system competitive with grid electricity.

A carbon tax of \$25, \$50, and \$75 per tonne CO_2 results in a 2.8%, 5.6% and 8.4% decrease in LEC, respectively. This suggests that carbon policy alone is not enough to make home tri-generation competitive with grid electricity, unless carbon is priced at significantly higher values.

The economic performance is sensitive to changes in energy prices. A 10% and 20% decrease in gasoline price results in an 8.2% and 16.3% increase in LEC. A higher gasoline price allows more credit, and thus improves the economics of tri-generation systems. A 10% and 20% increase in gasoline price (20% increase in price is equivalent to a gasoline price of \$3.74 gallon^{-1}) leads to an 8.2% and 16.3% decrease in LEC. A 10% and 20% increase in NG price leads to an 8.6% and 17.1% increase in LEC. Although changes in electricity price do not lead to significant changes in LEC, the economics of tri-generation systems is still sensitive to electricity price, since what matters is the difference between LEC and electricity price. A 20% increase in electricity results in a −0.74 ¢ kWh^{-1} difference between LEC and electricity price (LEC minus electricity price) and enable tri-generation system to compete with the conventional grid electricity, NG hot water heat and gasoline combination.

The home tri-generation system is not competitive with the conventional system of grid electricity, NG heat and gasoline, for the base case assumptions. However, sensitivity analysis shows that a 14% reduction in overall system capital cost (corresponding to a 42% reduction in the PEMFC sub-system cost), a \$3000 credit, or a 20% increase in gasoline price could enable home tri-generation to compete with the grid electricity, NG heat, and gasoline combination. A 20% decrease in NG price and a 20% increase in electricity price also enables tri-generation system to compete with the grid electricity, NG heat and gasoline combination.

5. Discussion of other issues

In addition to the simulation results, other considerations might impact the viability of home tri-generation, but are not quantified explicitly in our analysis. First, there are distributed generation benefits to consumers and utility companies. Use of small tri-generation systems mitigates the need to expand transmission and distribution capacity, gives consumers more control on power supply, and provides more reliable power. Second, the viability of tri-generation systems depends on regional conditions and energy prices. Our analysis used data for California, a region that does not have favorable heat demand profiles due to its temperate weather. Consequently, some of the generated heat is not used because of California's lower heat demand, compared with colder climates such as New York and Connecticut. Third, regions with low NG prices and high electricity prices would be more favorable for tri-generation. NG based home tri-generation offers modest (21%) reductions in CO_2 emissions compared to conventional technologies. Ultimately, using renewable energy sources for home tri-generation could lead to near-zero CO_2 emissions. We did not consider renewable feedstocks in this analysis, but relied on NG, which is the most likely option during early pre-commercial introduction of FCVs.

6. Conclusions

In this paper, we develop an interdisciplinary framework and an engineering/economic model (HTS model) to evaluate the design, and technical, economic, and environmental performances of tri-generation systems for co-production of residential electricity, heat, and hydrogen for refueling vehicles. We focus on NG based home tri-generation, but these methods can also be applied to other energy systems such as electrolyzer stations powered by the grid or renewable electricity.

The optimal FC sub-system size of a home tri-generation system is found to be 1.9 kW for both slow and fast refueling cases. For the base case assumptions (assuming an FC sub-system cost of \$2313 kW^{-1} and a 2 kW tri-generation system cost of \$13,745), the LEC is estimated to be 19.3–20.6 ¢ kWh^{-1}. The LEC is relatively insensitive to the FC sub-system size around a broad minimum centered at 1.9 kW: changing the system size by 1 kW increases the electricity cost by less than 2%. The optimal FC sub-system size is somewhat sensitive to the system capital cost and NG price, but less sensitive to electricity and gasoline prices.

We evaluate a range of 2 kW systems for home tri-generation, considering different operating strategies. We compare the cost of providing home electricity, heat and hydrogen transportation fuel with the tri-generation system to a conventional reference system using grid electricity, conventional NG technologies for hot water heat, and a gasoline fueled car. Home tri-generation is generally a more expensive option than the reference system. For the base case assumptions, the LEC with tri-generation is about 2.5–3.8 ¢ kWh^{-1} higher than the 16.8 ¢ kWh^{-1} grid electricity price. If instead, we assume the electricity price equals the grid price, and solve for the levelized hydrogen cost, which is found to be \$7.95 kg^{-1}. This is equivalent to a gasoline price of \$3.61 $gallon^{-1}$ on a cents per mile basis, accounting for the higher fuel economy of a FC car compared to a gasoline car. Moreover, a levelized hydrogen cost of \$7.95 kg^{-1} is highly competitive with the hydrogen cost from an early public hydrogen refueling station (recent research suggests that hydrogen can cost \$13–77 kg^{-1} from an early, underutilized station).

The results are sensitive to credits and changes in capital cost and energy prices, which have the potential to make home tri-generation competitive with conventional technologies.

For example, a 14% reduction in capital cost, a \$3000 credit, or a 20% increase in gasoline price could enable home tri-generation to compete with the conventional technologies (grid electricity, NG heat, and gasoline combination). This suggests that credits and policies could play an important role in accelerating the commercialization of home tri-generation, which will help bring down system capital cost. There is significant CO_2 emission reduction (20.52%) associated with home tri-generation compared to conventional technologies. Carbon taxes have a modest, positive impact on the economics of home tri-generation system (for a carbon tax of \$50/tonne CO_2, the LEC is reduced from 19.3 ¢ kWh^{-1} to 18.2 ¢ kWh^{-1}).

Overall tri-generation for home refueling has the potential to be included in hydrogen infrastructure plans or portfolio infrastructure solutions in California and other states or countries. It is competitive with other early options for fueling hydrogen cars, although it is difficult to compete with conventional technologies unless capital costs are reduced, or gasoline prices increase. In future work, we will analyze neighborhood refueling using tri-generation, since we expect the economy of scale would further improve its economic performance.

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References

[1] NRC, Transitions to Alternative Transportation Technologies — A Focus on Hydrogen, National Research Council of The National Academies, Washington, DC, 2008.
[2] K. Wipke, D. Casey, M. Veenstra, G. Stottler, DOE Annual Merit Review Proceedings: Technology Validation Presentations, Washington, DC, 2010.
[3] M.A. Nicholas, J.M. Ogden, An Analysis of Near-Term Hydrogen Vehicle Rollout Scenarios for Southern California, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-10-03, 2010.
[4] B.K. Gross, I.J. Sutherland, Hydrogen Fueling Infrastructure Assessment, GM R&D Center, 2007.
[5] M.W. Melaina, Turn of the century refueling: a review of innovations in early gasoline refueling methods and analogies for hydrogen, Energy Policy 35 (2007) 4919–4934.
[6] T.E. Lipman, J.L. Edwards, D.M. Kammen, Fuel cell system economics: comparing the costs of generating power with stationary andmotor vehicle PEM fuel cell systems, Energy Policy 34 (2004) 101–125.
[7] T.E. Lipman, C. Brooks, Hydrogen Energy Stations: Poly-Production of Electricity, Hydrogen, and Thermal Energy, UCD-ITS-RR-06-07, Institute of Transportation Studies, University of California, Davis, 2006.
[8] T.G. Kreutz, J.M. Ogden, Development of An Efficient, Low Cost, Small-Scale Natural Gas Fuel Reformer for Residential Scale Electric Power Generation, Final Report, Department of Energy, 2000 (DOE/ET/50534-1).
[9] B.A. Abbanat, Alternative Fuel Vehicles: The Case of Compressed Natural Gas (CNG) Vehicles in California Households, Institute of Transportation Studies, University of California, Davis, 2001.
[10] K. Kurani, D. Sperling, T. Turrentine, The Marketability of Electric Vehicles: Battery Performance and Consumer Demand for Driving Range, University of California, Davis, 1996 (UCD-ITS-RP-96-32).
[11] E.C. Heydorn, Annual Merit Review Proceedings: Technology Validation, Validation of an Integrated Hydrogen Energy Station, Washington, DC, 2010, 2010.
[12] M. Kaya, R. Rocheleau, M. Ewan, Presentation to the 2010 DOE Hydrogen Program Annual Merit Review, Washington, DC, 2010.
[13] A. Lutz, E. Stewart, S. Busquet, M. Ewan, R. Rocheleau, Case Study: The Hawaii Hydrogen Power Park Demonstration at Kahua Ranch, Sandia National Laboratories, Livermore, CA, 2010.
[14] B. Taylor, From test stations to commercialization within a decade at hydrogenics, Fuel Cells Bulletin 2004 (4) (2004) 10–14.
[15] http://www.h2mobility.org/ (accessed 24.08.10).
[16] H. Nagaoka, National Hydrogen Association Annual Conference, Honda R&D Co., Ltd., Automobile R&D Center, Sacramento, CA, 2008.
[17] Hydrogen Fuel Cell Vehicle and Station Deployment Plan: A Strategy for Meeting the Challenge Ahead-Progress and Next Steps, 2010.
[18] X. Li, J. Ogden, Modeling home refueling cogeneration systems as a new paradigm for hydrogen vehicles, in: Proceedings of the Fuel Cell Seminar & Exhibition (CD), Phoenix, AZ, 2008.
[19] Web dictionary of cybernetics and systems, http://pespmc1.vub.ac.be/ASC/Black_metho.html (accessed 24.08.10).
[20] J. Larminie, A. Dicks, Fuel Cell Systems Explained, 2nd ed., J. Wiley, Chichester, West Sussex, 2003.
[21] M.E. Gorman, T.F. Fuller, Proceedings of the Annual Automotive Technology Development Customer's Coordination Meeting, Dearborn, MI, 1997.
[22] K.T. Ooi, T.N. Wong, A computer simulation of a rotary compressor for household refrigerators, Applied Thermal Engineering 17 (1997) 65–78.
[23] X. Li, J. Ogden, K. Kurani, An overview of automotive home and neighborhood refueling, World Electric Vehicle Journal 3 (2009).
[24] A.D. Little, Fuel Cells for Building Applications: Market Analysis, Technology Status, and Program Plan Overview, vol. 2, 1994.

[25] EIA, U.S. Per Vehicle Average Miles Traveled, Vehicle Fuel Consumption and Expenditures, Energy Information Administration, 2001.
[26] EIA, Independent Statistics and Analysis, United States Energy Information Administration, http://www.eia.doe.gov/ (accessed 16.07.10), 2009.
[27] C.E. Thomas, J.P. Barbour, B.D. James, F.D. Lomax-Jr., Analysis of Utility Hydrogen Systems and Hydrogen, Airport Ground Support Equipment, Golden, CO, 1999.
[28] South Coast Air Quality Management District, Agenda No. 20. Board Meeting, date: July 11, 2008, http://www.aqmd.gov/hb/2008/july/080720a.htm (accessed: 13.06.10), 2008.