Understanding the Design and Economics of Distributed Tri-generation Systems for Home and Neighborhood Refueling: Residential Case Studies

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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, current lack of a hydrogen infrastructure is a major barrier for FCV 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 past experience of fuel infrastructure development for motor vehicles, innovative, distributed, and small-volume hydrogen refueling methods may be required to refuel FCVs in the near term. Among these small-volume refueling methods home and neighborhood level tri-generation systems stand out because of technology availability and their potential to alleviate consumer's fuel availability concern and other features attractive to consumers.

The objective of this paper is to provide a set of analytical tools for various stakeholders such as policy makers, manufacturers and consumers, to identify the optimal design and evaluate the economic and environmental performance of tri-generation systems for home and neighborhood refueling. An interdisciplinary framework and engineering/economic model are developed and applied to assess these systems. Major tasks include modeling steady state system performance, exploring the optimal design 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, government incentives and environmental cost are evaluated. Policy implications of the modeling results are also explored. Three case studies using California residential energy consumption data are presented.

Keywords: hydrogen, tri-generation, home and neighborhood refueling

1 Introduction

Although hydrogen fuel cell vehicle (FCV) technology has been making rapid progress, current lack of a hydrogen infrastructure is a major barrier for FCV 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.

Various infrastructure build-out strategies have been proposed to address the high cost and low utilization of early hydrogen infrastructure. One approach is focusing early FCV deployment (both vehicle and stations) in selected, concentrated geographic regions such as Los Angeles and New York [1, 2]. 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 are still issues.

In this paper we explore a different paradigm: use of 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 past experience of fuel infrastructure development for motor vehicles, innovative, distributed, and small-volume hydrogen refueling methods may be required to refuel FCVs in the near term. Among these small-volume refueling methods home and neighborhood level tri-generation systems stand out because of technology availability and their potential to alleviate consumer’s fuel availability concern and other features attractive to consumers.

Home and neighborhood refueling both have the potential to offer early 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 improved by co-producing valuable products: electricity and heat [3, 4, 5]. 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 [6, 7]**.**

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 small scale electrolysis and on-site hydrogen production using reformation of natural gas, because electricity and natural gas are commonly available in residential households. For electrolysis systems to be feasible, small, low cost electrolyzers will need to be developed. This paper will not evaluate refueling through electrolysis, but the analytical tools developed in this paper can be applied to electrolysis systems. For hydrogen production using natural gas, most demonstration projects use tri-generation systems. Very few, if any, companies are developing refueling-only home systems because of their high capital cost. Tri-generation systems are energy systems that are designed to meet the three energy needs (electricity, heat, and transportation fuel) of a typical household. Traditionally, these three energy needs are met by grid electricity, natural gas heat, and gasoline. A typical tri-generation system produces electricity and heat for buildings as well as hydrogen for vehicles by using a hydrocarbon such as natural gas or biogas as an energy source. More details on the mechanism of tri-generation systems are provided in section 2. Tri-generation systems are more cost competitive than stand-alone hydrogen refueling systems because they are configured to simultaneously provide electricity and heat for residences along with hydrogen for a vehicle. The capital cost of hydrogen production equipment is shared for production of heat and electricity.

Policy makers are currently assessing the status of market pull complementary policies and the need for additional incentives for FCVs. They are working on a California-specific infrastructure plan. Home and neighborhood refueling both have the potential to be included in the plan. However, before including these refueling methods in the portfolio infrastructure solutions, it is important to assess the feasibility of these methods and compare them with alternatives.

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 economic and environmental performance of tri-generation systems for home and neighborhood refueling. An engineering/economic model is developed and utilized in this paper to evaluate these systems. Major tasks include modeling steady state system performance, exploring the optimal design 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. Three case studies using California residential energy consumption data are presented.

Table 1: List of fuel cell tri-generation/cogeneration demonstration projects [4, 8, 9]

Project	**Dates**	**Partners**	**Project description**
Stuttgart Airport, Germany	Start date Jun., 2009	OMV (a major German fuelling station operator), Linde and Daimler	The station reforms natural gas to H2 on-site, and incorporates ion-compressor technology developed by Linde. Cars and electric buses powered by fuel cells can be refueled within minutes.
Billerica, Massachusetts, USA	Opened in Aug., 2008	Nuvera Fuel Cells' US Headquarters	The first hydrogen refueling station in Massachusetts; reforms natural gas to H2 on-site.
Osaka-prefectual office, Japan	Start date, Dec., 2007	Osaka Gas Co., Ltd.; JHFC; Ministry of Economy, Trade and Industry (METI)	The station reforms natural gas to H2 on-site, and is part of the Japan Hydrogen and Fuel Cell Project JHFC.
Korea Gas Research and Development Facility, Incheon, South Korea	Start date Jan., 2007	Hydrogenics Corp.; QuestAir Technologies Inc.; Harvest Energy Technology; KOGAS-tech (Korea Gas Technology Corporation)	The station reforms natural gas to H2 on-site, is capable of producing sufficient hydrogen to refuel approximately 20 FCVs.

Oakland, California	Opened August 2005	AC Transit, UTC Power, Chevron, Van Hool, ISE Research, DOE, NREL, ITS-UC Davis, Hyundai	Small scale steam reforming of natural gas; capable of dispensing up to 150 kg of hydrogen per day; Storage capacity-366 kg H2 at 6,250 psi, able to fuel a stationary fuel cell for power needs at AC Transit's maintenance facility.
The Toronto Hydrogen Energy Station, Toronto, Canada	Opened May 2005	Hydrogenics, Canadian Transportation Fuel Cell Alliance, City of Toronto, h2ea, Purolator	The world's second energy station; installed in 2003; with on-site H2 production, storage and dispensing capabilities; can produce 20 kg/day of H2.
Latham, New York H2 Home Energy Station	Opened November 2004	Honda R&D Americas, Plug Power	Designed to power a home, provide hot water and generate hydrogen fuel for refueling FCVs.
Torrance, California Home Energy Station	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 FCX fleet.
The Las Vegas Hydrogen Energy Station	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 FC system; a $10.8 million project.

2 Tri-Generation System Description

A typical tri-generation system is shown in Figure 1. A fuel reformer converts natural gas 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 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.

Tri-generation systems can operate under a number of possible strategies, described below.

- Stand alone: the system is not grid-connected. All energy needs can be satisfied with the system and natural gas supply.
- Grid-connected: the system is grid-connected and able to buy electricity from the grid when it is more economical to do so.
- Heat load following: the system operates to follow the heat load.
- Electricity load following: the system operates to follow the electricity load.

- Fixed refueling pattern: the system requires customers to refuel at certain times of day. The hydrogen storage unit can be eliminated or very small under this strategy.
- Flexible refueling pattern: the system allows customers to refuel at will. A certain amount of hydrogen storage is needed.

Operational strategies can significantly affect the optimal system design 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 for typical residential demand profiles, and avoids the high cost of meeting peak power demands with a stand-alone system). The case studies in this paper will evaluate different refueling patterns as well.

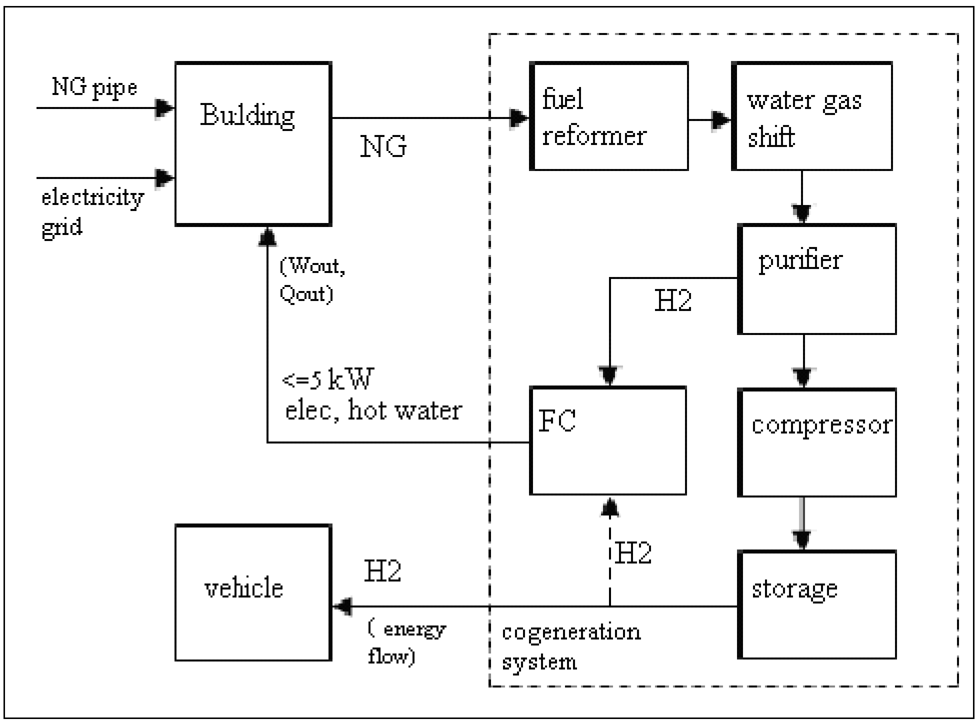


Figure 1: the schematic of a typical tri-generation system

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 thermodynamics, chemical engineering, economics, and consumer behavior research, and is illustrated in Figure 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 on the installation and operation of the systems. In the first stage, physical property data of energy systems and relevant theories are fed into the engineering modeling process. In the second stage, engineering economic analyses are conducted on the basis of the engineering modeling; 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.

Inputs to the engineering economic analyses include energy consumption data, energy prices, and other economic inputs. The last arrow highlights the outputs of the analyses. A model developed under this framework should allow us to compute the levelized costs of energy, whether it is in the form of electricity, heat, or hydrogen. System emissions are another important output. The optimal sizes of a system or components are also of interest to manufacturers and consumers. Several inputs are subject to high uncertainty, so sensitivity analyses are an important part of the analyses. In sub-section 3.2, an engineering/economic model developed based on the framework is introduced in great detail.

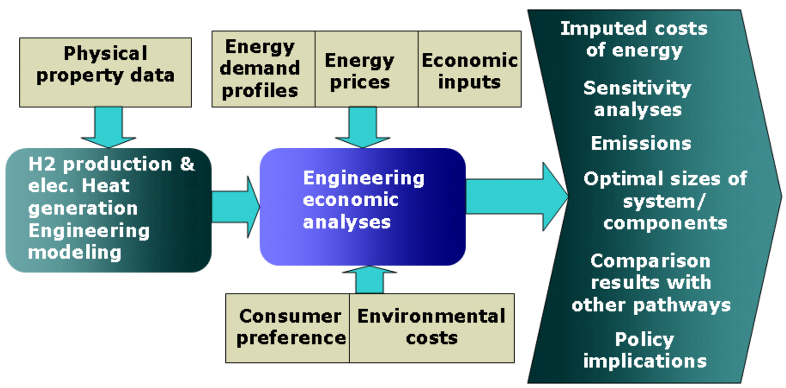


Figure 2: Interdisciplinary framework for analyzing tri-generation systems

3.2 The HTS (H2 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 in this paper. The model is developed utilizing a "grey box" modeling approach, which is a strategy for investigating a complex object with a certain level of knowledge or assumptions about its internal make-up, structure or parts. As shown in Figure 1, there are five major components 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 [10]. Each component is modeled based on thermodynamics, physics and other relevant engineering theories, and the efficiency of each component can be calculated. The efficiency of the entire system is the product of the efficiencies of all components. These efficiency parameters are key engineering inputs in later engineering/economic analyses. The efficiency curve of the FC system is shown in Figure 3. Figure 4 shows the AC electricity to NG efficiency curve for a 3 kW tri-generation system.

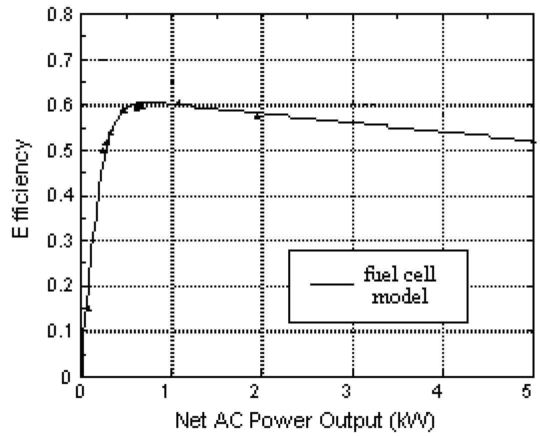


Figure 3: Efficiency of the fuel cell system (modified from: [5])

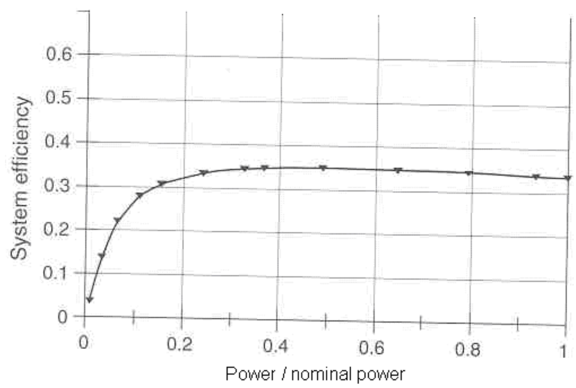


Figure 4: the AC electricity to NG efficiency curve
(source: [11])

Economic analysis is another major task of the model. Major 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 long does it take to repay the investment?
- 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

purchasing 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. This paper focuses on answering the following questions: how can the potential innovative benefits associated with home and neighborhood refueling be identified and quantified; and how can these benefits be incorporated into the model to better understand the opportunities and barriers toward the commercialization of these technologies?

In 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, for a particular system design and operational strategy, and specified demands and prices for electricity, heat, and hydrogen. An economically viable tri-generation system will have a positive net present value (NPV). To compete with conventional systems (electricity purchased from the grid, natural gas hot water heating, and gasoline or hydrogen purchased from a public refueling station), the tri-generation system should have a higher NPV than the conventional systems. Another approach is to estimate the levelized cost of one energy product (electricity) in terms of the other products (hot water heat, and hydrogen). 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 is the constant cost of each kWh that would be incurred over the life time of a tri-generation system. The levelized electricity cost can be compared to the price of grid electricity, as a metric for when the tri-generation system is competitive with the conventional system.

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

$$C_{\mathrm{elec}} = \mathrm{CRF} \times CC + CC_{\mathrm{o\&m}} \qquad (1)$$

C_{elec} is the annual cost of electricity ($);
CRF is the capital recovery factor;
CC stands for the present value of life cycle capital cost of a system ($);
$CC_{\mathrm{o\&m}}$ stands for annual operating and maintenance cost ($/yr).

Equation 1 can be written in greater detail as in Equation 2.

$$\begin{aligned} C_{\mathrm{elec}} &= \overline{R}_{\mathrm{elec}} \times \int P \mathrm{d}t \\ &= \mathrm{CRF} \times CC + c_{\mathrm{o\&m}} + cv_{\mathrm{o\&m}} \end{aligned} \qquad (2)$$

$\overline{R}_{\mathrm{elec}}$ is the levelized cost of electricity ($/kWh);

P is the hourly average electricity demand load (kW), and $\int P\mathrm{d}t$ is annual electricity demand (kWh/yr);

$c_{\mathrm{o\&m}}$ is fixed annual operating and maintenance cost (independent of the amount of energy produced) including labor, maintenance costs, and overhead ($/yr);

$cv_{o\&m}$ is variable annual operating and maintenance cost (depend on the amount of energy produced) including feed stocks, water, and chemicals ($/yr).

Equation 3 can be derived based on Equation 2.

$$\overline{R}_{elec} \times \int P\mathrm{d}t$$
$$= \mathrm{CRF} \times (CC\text{-}C_{MTP}) + c_{o\&m} + R_{NG} \times n_{NG} + \int R_{ele}\theta_1(P)\mathrm{d}t + \int R_{ele}\theta_2(P)\mathrm{d}t - c_{heat} - c_{transport} - t_{carbon}$$

$\theta_1 = P$, $P < 1/5\ P_{FC,\ max}$, turn down ratio of the FC system is 5; $\theta_1 = 0$, otherwise.
$\theta_2 = P - P_{FC,\ max}$, $P > P_{FC,\ max}$; $\theta_2 = 0$, otherwise.

(3)

Where,
C_{MTP} represents consumer's willingness to pay for home refueling service ($);
n_{NG} is the amount of natural gas consumed (kW);
R_{NG}, is the price of natural gas ($/kWh);
R_{elec} is the electricity price ($/kWh);
c_{heat} represents the annual credit of hot water heat, (based on what it would have cost to provide heat using a conventional natural gas based hot water system ($/yr);
$c_{gasoline}$ represents the annual credit of gasoline, based on what it would have cost to purchase gasoline from a public refueling station ($/yr);
t_{carbon} represents a carbon tax ($/yr).

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

c_{heat} and $c_{transport}$ 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 the consumers no longer need to buy hot water heat and gasoline or alternative transportation fuels. Therefore, c_{heat} and $c_{gasoline}$ are included in Equation 3. c_{heat} is the product of annual natural gas consumption, the efficiency of how water system, and natural gas price. $c_{gasoline}$ can be calculated by multiplying annual gasoline consumption with gasoline price.

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, natural gas heat, and gasoline combination pathway, and the cost is then included in the economic analysis. t_{carbon}, in equation 3 can be calculated by multiplying the unit carbon tax with the CO_2 emission reduction/increase. Additionally, previous research and documents on consumer preferences are reviewed and can be integrated into the modeling process. First, costs and functional, psychological and social benefits associated with adopting home and neighborhood refueling for consumers is identified. Second, those benefits and non-monetary costs are discussed and partially quantified, and consumers' WTP for home and neighborhood refueling systems can be incorporated into the modeling process through variable C_{WTP} in Equation 3 [6, 7, 12].

Equation 4 is derived from Equation 3 after simple manipulation, and is the key equation used to calculate the levelized cost of electricity for a particular tri-generation system configuration.

$$\overline{R}_{elec} = \frac{CRF \times (CC - C_{WTP}) + C_{o\&m} + R_{NG} n_{NG} + \int R_{ele} \theta_1 (P) dt + \int R_{ele} \theta_2 (P) dt - c_{heat} - c_{transport} - t_{carbon}}{\int P dt} \quad (4)$$

3.3 Energy Data and Other Inputs

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 for a representative single family residence in northern California. Figure 5 shows the ordered hourly electricity load profile. A hot water demand profile for the whole year (8760 hours) is not available, because very few agencies, if any, monitor hot water demand at this detailed level. As a result, a 24-hour hot water demand profile is used to represent the whole year. 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, for a typical residence the total electricity consumption is approximately double the hot water energy consumption, and the two peaks of electricity hourly profile match that of the hot water profile. Second, a hot water tank can be a buffer for small mismatch in electricity and hot water demand. Therefore, if tri-generation systems operate with an electricity load following strategy within its operation range, sufficient heat will be available for recovery [5]. The hot water storage currently available in residences accommodates the variations in demand. Figure 6 shows a 24-hour hot water demand profile. Space heating energy is not considered in this study, because it's peaks and magnitude do not match the electricity demand profile. Not much tri-generation benefit is expected to be achieved by providing space heating.

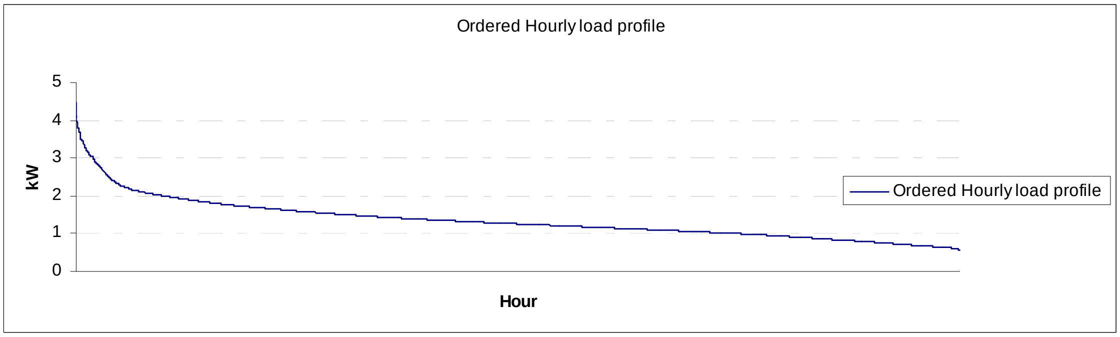


Figure 5: ordered hourly electricity load profile

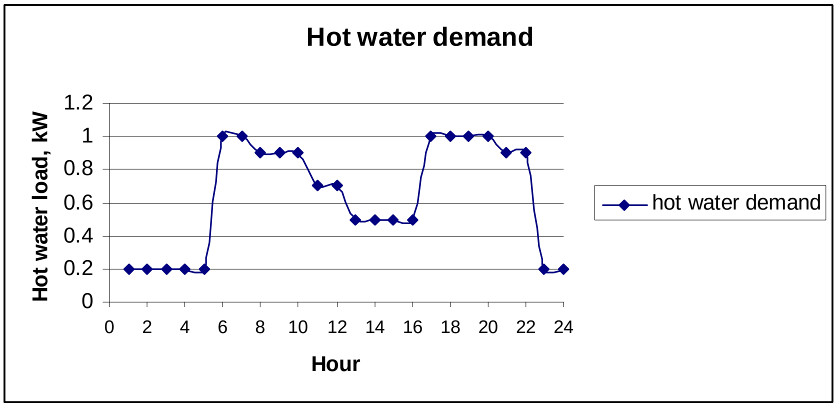


Figure 6: hot water demand profile (source: [3, 13])

Transportation energy consumption is as large as the electricity consumption [14], 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 kilogram of H_2 for a FCV. Table 2 summarizes the energy demand data.

Table 2: 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	number of days
Electricity	1.35	11889.54	4.47	0.48	0.57	366
Hot water	0.64 (2.30 MJ/h)	5599.8 (20.16 GJ)	1	0.2	0.33	366
Hydrogen	n/a	10800 (324 kg)	n/a	n/a	n/a	366
Gasoline	n/a	21600 (601 gal)	n/a	n/a	n/a	366

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 3 shows some of the inputs used in this paper. Table 4 presents more details on component costs.

Table 3: Some engineering/economic inputs (costs are in 2008 dollar)

Engineering inputs	Efficiency curves as shown in Figures 3 and 4; hydrogen utilization factor, 0.85.
Price of energy	Based on the PG & E electricity and natural gas rate data for 2008, an electricity price of 16.8 ¢/kWh and a residential CNG vehicle rate of \$1.09/therm (\$0.0372 /kWh) are used. A gasoline price of \$3.12 /gallon is used based on EIA data [15].
Costs assumptions	The capital cost of a system is the sum of components (e.g., reformer, FC system, and the compressing and dispensing system) costs; each component cost is a function of the component size. The FC stack needs to be replaced every 5 years.
Other economic assumptions	The system life is 10 years, and the CRF is 0.146 with a discount rate of 8%.

Note: a. FC system efficiency is defined as: "electricity out/H_2 in"; b. parasitic load is considered in the modeling process.

Table 4: System component costs (in 2008 dollar)

Component	Cost
Natural gas reformer	4616+ 129 $P_{ref,max}$, ($P_{ref,max}$ is the capacity of the reformer in kW)
PEM fuel cell stack	1.1 * (((454.45 - 105.4) / 10 + 17.56 * 0.6) * $P_{FC,max}$ * (1 + 0.06) ^ 5 / 0.625 + 428.5), ($P_{FC,max}$ is the capacity of the FC stack in kW)
Ancillary components	2980.2 + 35.654 * $P_{FC,max}$ – 0.0422 * $P_{FC,max}^2$
inverter/controller	542 + 169 $P_{FC,max}$
Storage System	284 N_t + 192*N_{fcv}*H_{fcv}*S_f /U_c (N_t- the number of tanks in the cascade filling storage system, N_{fcv}- the number of fuel cell vehicles supported by the system, H_{fcv} - the average daily hydrogen consumption by one FCV, S_f - the total cascade storage fraction of average daily demand, and U_c = the hydrogen utilization fraction.)
Compressor	1849.324+116.86 P_{comp}, (P_{comp} is the capacity of the compressor in kg/hr)
Dispenser	371.705+34.547*$P_{FC,max}$ (for overnight, slow-fill); 474.471+44.098*$P_{FC,max}$ (for flexible fast-fill)
Hot water cogeneration	0
Installation Costs Annual service	500 +4 $P_{ref,max}$ 125

Note: the cost data is derived based on data from [16], the cost estimation is based on a 10,000 units production volume.

4 Case Studies

4.1 The Optimal Design of a Tri-Generation System for Home Refueling

The optimal design 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 the optimal design of the 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 design is explored using the HTS model for two systems. 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.

The brute force exhaustive search algorithm for finding the optimal design

Given the assumptions, the optimal design is determined by selecting the optimal size of the FC system, and the brute force exhaustive search algorithm is used for finding the optimal design. The simulation results for the slow and fast refueling systems are illustrated in Figure 7. For the slow refueling system, the lowest levelized electricity cost point (19 cents/kWh) on the curve, where the capacity of the FC system is around 1.9 kW, corresponds to the optimal design. There is a tradeoff between the capacity factor (capital utilization), system size and the power purchased from the grid. As expected the optimal size of the system is in between the maximum and minimum electricity load. For the fast refueling system, the lowest levelized electricity cost is 20.2 cents/kWh, and the optimal design is 1.9 kW as well. It is not surprising that providing fast refueling service increases the levelized electricity cost, since fast refueling requires hydrogen storage and extra cost on a dispenser.

In simulating one can model the discrete system size with a very small step difference, such that the system size can be almost continuous. However, in reality the commercial systems manufactured would be discrete sizes with much larger step difference. For example, a manufacturer may make systems of size 2 kW, 2.5 kW, 3 kW, etc. It is unlikely that they will make systems of size 2.1 kW, 2.2 kW, 2.3 kW, etc. Therefore, it is necessary for us to examine the impact of sub-optimal system sizing. In the slow refueling system case, the cost penalty of optimal system size mismatch is small. Assuming a 0.5 kW step, the two sub-optimal sizes nearest to 2 kW (and 1.9 kW) are 1.5 kW and 2.5 kW, and there is a 0.27% and 0.66% increase in levelized electricity cost associated with these sizes, respectively. With a 1 kW step, the two sub-optimal sizes nearest to 2 kW are 1 kW and 3 kW, and there is a 1.74% and 1.93% increase in levelized electricity cost, respectively [5]. In the fast refueling system case, the levelized electricity cost of sizes 1.5 kW and 2.5 kW increases 0.26% and 0.62% respectively, compared with a 2 kW system. With a 1 kW step, the levelized electricity cost of a 1 kW and 3 kW system increases 1.63% and 1.82%, compared with a 2 kW system.

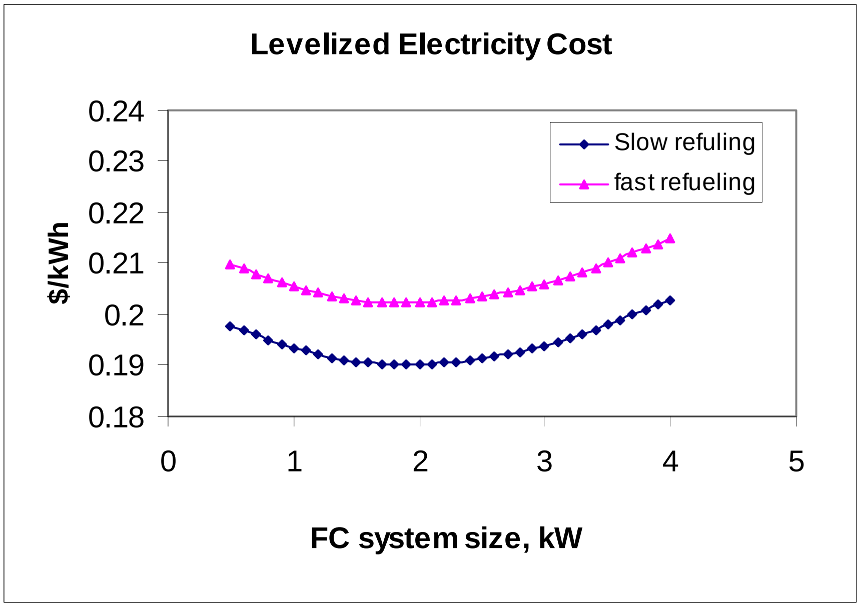


Figure 7: levelized electricity cost vs. FC system size for a slow and fast refueling system

4.2 The Economics of Operating a 2 kW Slow Refueling Tri-Generation System

This case study evaluates a 2 kW slow refueling tri-generation system because it is the sub-optimal design found in sub-section 4.1 (the optimal design is 1.9 kW) given the energy consumption data, energy prices and other engineering and economic inputs. The system is assumed to be grid-connected with an electricity load following strategy and overnight slow refueling pattern. No hydrogen storage unit is configured in the system. The levelized cost of electricity and the annual energy cost of the household are calculated to assess the economic performance of the system. The annual CO_2 emissions are calculated as well. In addition, these results are compared with the economic and environmental performance of two other pathways: the traditional grid electricity, natural gas heat, and gasoline combination and the pathway of grid electricity, natural gas heat, and hydrogen purchased from an early public station.

The simulation results show that the levelized electricity cost is about 19 cents/kWh with a capital cost of $13497.8. The levelized electricity cost is 2.2 cents/kWh higher than the 16.8 cents/kWh annual CA electricity price. The annual electricity cost from a tri-generation system is $ 2259, while buying electricity from the grid is $ 1997.4. There is a 13.1% or $261.6 increase in the annual cost using tri-generation systems. In addition, there is a 20.52% or 2892.1 kg reduction in annual CO_2 emission.

The HTS model allows us to evaluate the economic impact of various credits and capital cost reduction on purchasing a tri-generation system. The credit can be feebate, tax incentive, or other credits. A $3000 credit is included in the model to evaluate its impact. This $3000 credit is chosen because such a program has been implemented in the commercialization of home refueling systems for compressed natural gas vehicles [17]. Simulation results show a significant reduction in the levelized and annual electricity cost with the credit. The levelized electricity cost with credit is about 15.3 cents/kWh. The annual electricity cost of a tri-generation system is

$1819.1. There is a 19.47% or $439.9 decrease in the annual cost compared with before the credit, and an 8.93% or $178.3 decrease in the annual cost compared with the option of purchasing grid electricity and natural gas heat and gasoline.

The sensitivity analysis on capital cost reduction and energy price is also performed. A 20% capital cost reduction results in a levelized electricity cost of 15.6 cents/kWh, and an annual electricity cost of $1854.8. There is a 17.89% or $404.2 decrease in the annual electricity cost.

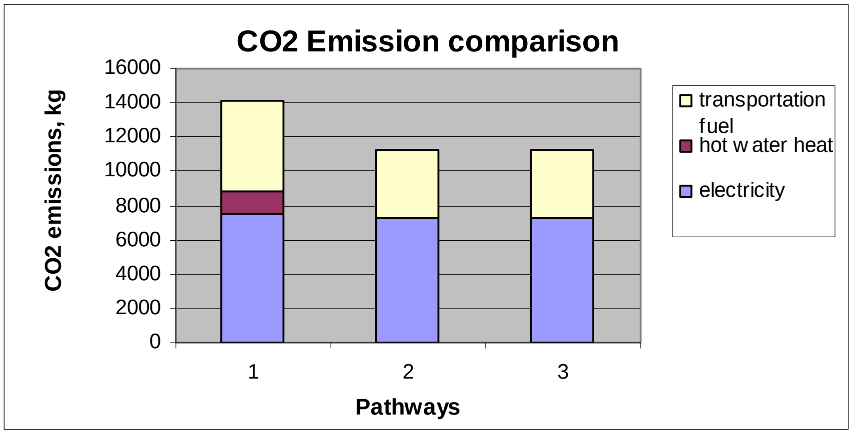
Simulation results show that a levelized hydrogen cost of $7.14/kg can be achieved using a tri-generation system given the electricity and NG price in table 3. It takes a gasoline price of $3.25/gallon for a tri-generation system to be competitive given energy consumption data and current prices, which is only slightly higher than the $3.12/gallon CA average gasoline price in 2008. This hydrogen cost is highly competitive with the option of grid electricity, natural gas heat and purchasing hydrogen from an early hydrogen station. For instance, Nicholas and Ogden estimated that the levelized cost of hydrogen for three time periods in Los Angeles:

- $77/kg in 2009-2011, 636 FCVs and 8-16 stations (using an average of 445 kg H2/d);
- $37/kg in 2012-2014, 3442 FCVs and 16-30 stations (using an average of 2410 kg H2/d);
- $13/kg in 2015-2017, 25,000 FCVs and 36-42 stations (using an average of 17,500 kg H2/d) [18].

4.3 The Economics of Operating a 2 kW Fast Refueling Tri-Generation System

This case study evaluates a 2 kW fast refueling tri-generation system. The system is assumed to be grid-connected with an electricity load following strategy and fast refueling pattern. A hydrogen storage unit is configured in the system to allow flexible fast refueling and trips longer than daily commute.

The simulation results show that the levelized electricity cost is about 20.2 cents/kWh with a capital cost of $14537.73. The levelized electricity cost is 3.4 cents/kWh higher than the 16.8 cents/kWh annual CA electricity price. The annual electricity cost from a tri-generation system is $ 2401.7. There is a 20.24 % or $404.3 increase in the annual cost compared with purchasing electricity from the grid, and a 6.32% or $142.7 increase compared with the slow refueling tri-generation system. The annual CO_2 emission reduction is the same as with the slow refueling tri-generation system (a 20.52% or 2892.1 kg reduction). Figure 8 presents a comparison of CO_2 emissions in three cases.



Note: 1-electricity+NG heat + gasoline; 2-slow refueling system; 3-fast refueling system
Figure 8: CO2 emission chart

With a $3000 credit, the levelized electricity cost is about 16.47 cents/kWh, and the annual electricity cost is $1958.2. There is an 18.47% or $443.5 decrease compared with before the credit. A 20% capital cost reduction results in a levelized electricity cost of 16.58 cents/kWh, and an annual electricity cost of $1971.3. There is a 17.92% or $430.4 decrease in the annual cost after the cost reduction. In addition, a levelized hydrogen cost of $7.62/kg can be achieved.

5 Conclusions

In contrast to the approach of focusing early hydrogen station and FCV deployment in selected, concentrated geographic regions and building an initial sparse network of hydrogen stations near early adopters, this paper explores a different paradigm: use of home and neighborhood refueling as a path toward commercializing FCVs. Analytical tools including an interdisciplinary framework and an engineering/economic model are provided and demonstrated for various stakeholders to evaluate the economic and environmental performance of tri-generation systems for home and neighborhood refueling. These tools can also be applied to other energy systems such as electrolyzer stations powered by grid or renewable electricity.

The results of the first case study indicate that a 0.5 kW step difference in system size significantly decreases the possibility of cost penalty from optimal system size mismatch, compared with a 1 kW step difference. Manufacturers need to take this into consideration when forming their manufacturing strategy. The results can also guide consumers to select the systems that best suit their energy needs.

The results of the second case study demonstrate that given current California energy consumption data and energy prices home tri-generation is slightly more expensive than the grid electricity, natural gas heat, and gasoline combination, but more economically competitive than the grid electricity, natural gas heat, and purchasing hydrogen from an early public station combination. Furthermore, although before any credit the levelized electricity cost is 2-3 cents/kWh higher than CA average electricity price and the annual electricity cost is $261.6 higher than the annual cost of the grid electricity, natural gas heat, and gasoline combination, other consideration and benefits still make tri-generation systems attractive and potentially competitive. First, California does not have favorable demand profiles due to its temperate weather, and less heat is recovered to fully take advantage of tri-generation benefits compared with places such as New York and Connecticut. Second, the electricity to natural gas price ratio used in this paper is not favorable to tri-generation systems. A more favorable ratio can be used and is practical. Third, there is convenience, security and other perceived benefits associated with home refueling, which are attractive to consumers. Fourth, a $3000 credit and a 20% reduction in capital cost significantly improve the economics of a 2 kW tri-generation system. Various credits and can play an important role in accelerating the commercialization of the tri-generation refueling method. Last but not least there is significant CO_2 emission reduction (20.52%) associated with home tri-generation systems.

Overall tri-generation systems for home and neighborhood refueling both have the potential to be included in hydrogen infrastructure plans or portfolio infrastructure solutions in California and other states or countries. This is particularly true for neighborhood refueling using tri-generation systems, since we expect the economy of scale would further improve the economic performance of tri-generation systems. Although a detailed analysis of tri-generation systems for neighborhood refueling is not provided in this paper, the analysis is underway and will be presented and published by the authors soon.

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