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Understanding The Design And Performance Of Distributed Tri-Generation Systems For Home And Neighborhood Refueling

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DISSERTATION

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To the loving memory of my father.

Xuping Li
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Understanding The Design And Performance Of Distributed Tri-Generation Systems For Home And Neighborhood Refueling

Abstract

The potential benefits of hydrogen as a transportation fuel, such as zero tailpipe emissions from vehicles and the diversity of energy sources will not be achieved until hydrogen vehicles capture a substantial market share. 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 low utilization in the near term discourages private and public investment. 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 that produce electricity and heat for buildings, as well as hydrogen for vehicles stand out because the technology is available, initial capital investment is modest, and it 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, and thus may prove also to be a desirable long term refueling option for consumers.

The objectives of this dissertation are twofold: to provide analytical tools for stakeholders such as policy makers, manufacturers and consumers to analyze tri-generation and similar energy systems in a systematic way; and to apply these tools to case studies to understand the design and technical, economic, and environmental performances of tri-generation systems for home and neighborhood refueling.

I first present a historical review and comparison of home and neighborhood refueling methods for a wide range of motor vehicles. Analytical tools including an interdisciplinary engineering /economic model are then developed for the detailed assessment of tri-generation systems for home and neighborhood refueling. Consumer’s preferences and willingness to pay (WTP) for home and neighborhood refueling systems along with the environmental cost are discussed and incorporated into the model.

I apply these analytical tools to case studies in two categories: home refueling tri-generation systems for a single-family residence; and neighborhood refueling tri-generation systems for multiple nearby households. In each case study, I explore the optimal design of tri-generation systems, which is defined as the determination of system components sizes that allow a tri-generation system to meet the three energy needs with minimal life cycle cost from a consumer's perspective. I also evaluate and compare the technical, economic, and environmental performances of tri-generation systems with two alternatives: the business as usual (BAU) reference system, in which households purchase grid electricity, natural gas (NG) for hot water, and gasoline fuel; and the projected reference system, in which households purchase grid electricity, NG for hot water, and hydrogen fuel from an early public station. A public hydrogen station is different from home and neighborhood refueling because of its scale and location.

I modeled system operation, exploring the optimal size of all components of the system, based on the cost of energy products: electricity, heat and hydrogen. I also

compared the cost of energy products and CO_2 emissions of a 2 kW (home refueling) and 6.5 kW (neighborhood refueling) tri-generation system with alternatives such as the two reference systems mentioned above. A sensitivity analysis was conducted with respect to uncertainties in energy prices, capital cost reduction (or increase), government incentives and environmental cost.

Overall tri-generation for home and neighborhood refueling has the potential to be included in hydrogen infrastructure plans or portfolio infrastructure solutions in California and other states or countries. It is economically competitive with early public stations for fueling hydrogen cars. The small capacity of the home and neighborhood tri-generation systems (relative to a public hydrogen station) and the valuable co-products helps address the low utilization problem of hydrogen infrastructure while hydrogen vehicle demand is low. In addition, although home tri-generation systems are difficult to compete economically with the BAU reference system unless capital costs are reduced, or energy prices change such as increasing gasoline price, neighborhood tri-generation systems offer better economic performance than the BAU reference system.

Future research might include comparisons of regions with significantly different energy demand profiles to see how the performance of tri-generation systems varies with demand profiles, the use of renewable feedstocks for the tri-generation systems, and viable business models for neighborhood tri-generation systems.

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Chapter 1: Introduction

Hydrogen as a transportation fuel has many attractive potential benefits including zero tailpipe criteria pollutants and CO_2 emissions from vehicles[1], and flexible sources of transportation energy, since hydrogen can be produced from a variety of primary sources including fossil fuels, renewable energy and nuclear power [1, 2]. Hydrogen fuel cell vehicles (FCV) also have range and refueling time comparable to a conventional gasoline vehicle. Therefore, range and refueling time are not expected to be an issue for FCVs in terms of consumer acceptance compared with battery electric vehicles (BEVs) [1, 2]. However, the potential benefits of hydrogen as a transportation fuel will not be achieved until hydrogen vehicles capture a substantial market share.

FCVs are slated for introduction in North America, Europe and Asia over the next few years due to their potential benefits. Hydrogen refueling infrastructure is a key issue for the rollout of these early fleets. However, despite the rapid progress in FCV technology such as improvements toward FC stack durability and FCV range [3, 4], lack of refueling infrastructure worldwide is still daunting to automobile companies and 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

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[1] This is important in that if the hydrogen is made from renewable sources, there will be no net carbon emissions associated with the hydrogen fuel production and use of the vehicle.

similar to the existing gasoline station network[2] and low utilization of the network in the near term discourages private and public investment and slows infrastructure deployment [5].

A few infrastructure build-out strategies have been proposed to initiate FCV adoption [5, 6]. One example approach is focusing early FCV deployment (both vehicles and stations) in selected, concentrated geographic regions such as Los Angeles and New York [5, 7]. More specifically, an initial sparse network of public hydrogen stations is located near early adopters in a limited number of regional "clusters." "Clustering refers to the focused introduction of hydrogen vehicles in defined geographic areas such as smaller cities (e.g. Santa Monica, Irvine) within a larger region (e.g. Los Angeles Basin). By focusing initial customers in a few small areas, station infrastructure can be similarly focused, reducing the number of stations necessary to achieve a given level of convenience" as measured by the travel time from home to the nearest station and the 'diversion time.' [5] Although clustering hydrogen station placement can improve consumer accessibility to hydrogen fuel, the high cost of building the hydrogen station network and low utilization in the near term are still issues, which discourage investment. Clustering allows less hydrogen stations to be built for early FCV adopters for similar refueling services compared with the gasoline station network, but it would still be expensive. [5]

In this dissertation, I explore a different hydrogen infrastructure deployment strategy: use of small-scale home and neighborhood refueling as a path toward

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[2] Here, "similar" is in terms of refueling experience for drivers such as refueling time, accessibility, and billing. A more sparse hydrogen network would suffice for early infrastructure, but it would still be expensive.

commercializing FCVs. Based on past experience of fuel infrastructure development for motor vehicles including gasoline and compressed natural gas (CNG) vehicles, innovative, distributed, an d small-volume hydrogen refueling methods may be required to refuel FCVs at least in the near term [8, 9]. For instance, CNG is currently available at approximately 1,300 refueling stations in 46 states in the U.S, which is less than 1% of the 170,000 gasoline stations that exist nationally [10]. In addition, some of these 1,300 CNG refueling stations are commercial or for fleet, rather than as retail stations. Drivers of CNG vehicles have complained of refueling access, billing, and location problems [11]. Lack of refueling infrastructure is an important reason that the number of CNG vehicles on the road grows only slowly, given the fact that the cost and performance of a CNG vehicle is comparable to gasoline vehicles. For example, based on the official website of American Honda Motor Co., Inc, the 2011 Honda Civic CNG car is only about $1500 more expensive than the 2011 Civic Hybrid, $25,500 v.s. $24,000, and has a comparable refueling time and a range of 220 miles. The CNG car also has lower cents per mile fuel cost. Some CNG car owners have bought home refueling systems to refuel their cars for convenience [11-13].

Among small-volume refueling methods for FCVs, home and neighborhood tri-generation systems stand out because the technologies are available, have potential to alleviate the consumer’s fuel availability concern. More importantly, home and neighborhood tri-generation systems have the potential to serve an early population of vehicles with less cost than to build an extensive network of hydrogen stations.[3] This hypothesis is based on two main facts. First, the small capacity of the systems allows

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[3] Although with home and neighborhood refueling systems FCV owners still need some public stations to facilitate long distance travel, the number of stations will be significantly reduced with the home and neighborhood refueling systems.

them to be installed wherever small hydrogen demand is without stranded investment. Second, the capital costs of the systems are shared by other energy products such as electricity and heat. This hypothesis will be tested later in this dissertation. In addition, home and neighborhood refueling has features attractive to consumers such as convenience and security to refuel at home or within the consumers' neighborhood [11, 14].

A typical tri-generation system produces electricity and heat for buildings as well as hydrogen for vehicles by converting a hydrocarbon such as natural gas (NG) or bio-methane [15]. The economic performance of small-volume hydrogen refueling systems can be improved by co-producing valuable products: electricity and heat [15-17]. There are a number of ongoing demonstration projects of tri-generation systems and FC combined heat and power (CHP) systems [18]. Table 1.1 provides a list and description of these projects. Current technologies for FCV home and neighborhood refueling focus on on-site hydrogen production using reformation of NG, because NG is commonly available in households. More details on tri-generation systems are provided in Section 4.1.

Table 1.1

List of FC tri-generation/cogeneration demonstration projects (source: [18])

Project	Dates	Partners	Project description

Fountain Valley Station Orange county Sanitation District, CA [19]	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 d^{-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, CO2: < 2 ppm).
Hawaii Hydrogen Power Park [20, 21]	Construction 2003-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 Jan 2013.
The Toronto Hydrogen Energy Station, Toronto, Canada [15, 22]	Installation begins in August 2003	Hydrogenics, Canadian Transportation Fuel Cell Alliance, City of Toronto, h2ea, Purolator	The world's second hydrogen tri-generation energy station; with on-site H_2 production, storage and dispensing capabilities; can produce power; can produce 20 kg d^{-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, CO2: < 1 ppm).
Latham, New York H_2 Home Energy Station [23, 24]	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 [15, 24]	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 [15]	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/cogeneration interest in Europe (e.g., Britain and Germany) and Asia (e.g., Japan and South Korea) as well; for example, in Japan thousands of residential FC based cogeneration systems (also called Micro-combined heat and power system, m-CHP system) have been installed as of 2010 [25].

Policy makers are currently assessing the status of market pull complementary policies (such as the Zero Emission Vehicle regulation in California and other states) and the need for additional incentives for FCVs. For example, the California Fuel Cell Partnership is working on a California-specific infrastructure plan to provide fuel availability to zero emission vehicles [6]. Home and neighborhood refueling both have the potential to be included in the plan (recent plans have made mention of these technologies, but have not seriously considered them for implementation [6]). However, before including these refueling methods in the portfolio of infrastructure solutions, it is important to assess their feasibility and compare them with alternatives.

This dissertation provides analytical tools for various stakeholders such as policy makers, manufacturers, and consumers, to assess home and neighborhood refueling methods for FCVs in a systematic way. We develop an interdisciplinary framework and an engineering/ economic model, and apply the framework and model to case studies in the Northern California Sacramento area. The case studies showcase the capabilities of these tools, and provide independent assessment of the technical, economic, and environmental performances of home and neighborhood refueling methods for FCVs.

The dissertation is organized as follows. Chapter 2 presents an overview and comparison of home and neighborhood refueling for a wide range of motor vehicles using different fuels. Chapter 3 summarizes the main research questions related to home and neighborhood refueling for alternative fuel vehicles, and defines the scope of this dissertation. Chapter 4 describes the methodology of this study. The mechanism of a typical tri-generation system is illustrated, and the analytical tools we developed in this study are described. Chapter 5 presents case studies of home refueling for single family residences. Chapter 6 presents case studies of neighborhood refueling for multi-family residences. Chapter 7 discusses considerations that might impact the viability of tri-generation systems, but are not quantified explicitly in our analysis. Chapter 8 summarizes the findings and conclusions from this study and suggests topics for future work.

Chapter 2: An Overview of Automotive Home and Neighborhood Refueling

2.1 Background

Chapter 2 presents a historical review and comparison of home and neighborhood refueling methods for a wide range of motor vehicles using different fuels. The home refueling experience of these vehicles and consumer preferences and response to these methods are discussed. Furthermore, the important questions, challenges, and opportunities of a home and neighborhood refueling strategy for alternative fuel pathways are explored.

Home refueling for private vehicles is not a new idea; between 1900 and 1915, a variety of home refueling options were introduced to early gasoline vehicle owners. These early home refueling outfits addressed the fuel availability concern of gasoline-vehicle drivers and featured convenience and reduced trips to public refueling facilities [9, 26]. Home refueling methods played an important role during the introduction of gasoline vehicles before large, public gasoline stations became dominant. Neighborhood refueling, which is intermediate in scale between home and large public station refueling, serves 10-20 vehicles per day and has less history. In addition to gasoline vehicles, the history of home refueling for motor vehicles also includes compressed natural gas (CNG) vehicles, battery electric vehicles (BEV), plug-in hybrid vehicles (PHEV), and FCVs.

2.2 A Historical Review of Home Refueling Methods

2.2.1 Home Refueling for Gasoline Vehicles

Because large, public gasoline stations have been the dominant refueling method for gasoline vehicles for a long time, it is easy to forget that home refueling once helped address concerns for fuel availability. Early home refueling outfits removed the driver's concerns about fuel availability, reduced trips to refuel vehicles, and offered convenience, and security of refueling at home to early vehicle owners, before a convenient network of large, public gasoline stations became available.

Early gasoline home refueling outfits typically included a private pump located in the garage and connected to an underground tank. A number of home refueling configurations were introduced between 1900 and 1915. The large variety of models supplied suggests that there was a significant clientele [9, 26]. Gasoline home refueling outfits exited the market when convenient, public stations offering cheaper gasoline became available. The reasons for gasoline vehicle owners to switch to large, public gas stations might have included the cost and difficulty of installation and maintenance, risk of fire or spills, and the relatively higher fuel cost associated with each driver maintaining their own home refueling facilities [9].

Home refueling played an important role in facilitating gasoline vehicles during early market penetration. Home refueling together with other small capacity, dispersed, non-station refueling methods such as mobile refuelers, addressed the concerns for fuel availability and made widespread use of gasoline vehicles possible before a convenient network of large, public gasoline stations became available. As pointed out in [9], the takeoff period for large, public gasoline stations occurred between 1915 and 1925, after the takeoff period for gasoline vehicle mass production, which is around 1910. During the transition period in between these two takeoff periods, small volume refueling methods addressed the fuel availability issues.

An important analogy from the early development of the gasoline station network is that innovative, small volume, and widely available refueling methods including home and neighborhood refueling may be necessary during the introductory periods of alternative fuel vehicles (AFVs), although the technologies, consumer experience and expectations, and regulatory environment are much different today compared with one century ago. Furthermore, home refueling offers a few attractive features other non-station refueling methods and a sparse public station network could not offer including reduced trips to refuel vehicles, convenience, and security of refueling at home, which may be appealing to some consumers [14].

2.2.2 Home Refueling for Compressed Natural Gas Vehicles

In early 1980’s, there was a push for the use of CNG vehicles in North America due to environmental and energy security concerns, and the economic viability of using NG as a transportation fuel. Although a dramatic increase in the NG to oil price ratio in 1987 stopped the push, the number of CNG vehicles on the road continued to grow slowly in the U.S. [8] By the end of 2010, around 112,000 CNG vehicles were operating in the U.S, and around 12,674,402 CNG vehicles were operating worldwide [27].

Lack of refueling infrastructure was one of the main barriers to the commercialization of CNG vehicles in the US. Under a collaborative endeavor of the government and private sector, there has been some investment in creating a CNG infrastructure system, although the investment was limited [8]. As mentioned in Chapter 1, the CNG refueling stations in the U.S. is currently less than 1% of the 170,000 gasoline stations [10]. Further, the CNG refueling locations tend not to be at commercial gasoline stations, but to be located in fenced facilities that each required users to have an account. With this low level of service and convenience, it is not surprising that drivers of CNG vehicles in southern California in the early 2000s uniformly complained of access, billing, and location problems related to refueling their vehicles [11]. Similar to the situation with gasoline vehicles a century ago, home refueling systems entered the market to partially solve the problem of fuel availability for CNG vehicles. CNG vehicle owners can now refuel their cars at home by installing a home refueling appliance, which consists of a small compressor connected to the home’s NG supply, and dispensing equipment. CNG vehicle owners can refuel their vehicles at home using these appliances and avoid some, if not all, trips to a CNG refueling station [28].

Beyond partially solving the problem of CNG availability; home refueling can provide the convenience and security of refueling at home, which may be an attractive feature to some consumers [14]. The potential of home refueling has drawn some attention from public decision makers as well. Recognizing the potential of home refueling for facilitating CNG vehicle sales, in 2005 the South Coast Air Quality Management District (AQMD) and the California Mobile Source Air Pollution Reduction Review Committee (MSRC) started to provide financial incentives to assist consumers in covering 57% of the cost of purchasing a new CNG home refueling appliance. An incentive is also offered for leasing a home refueling appliance. The program was recently renewed due to positive response and high demand [13]. Studies of consumer response to these incentives and the impact of them on home refueling for CNG would provide valuable data and analogies for other alternative fuel pathways. However, very few (if any) such studies are underway.

2.2.3 Home Refueling for Battery Electrical Vehicles

Since the late 1980s, BEVs have been promoted in the U.S. through a number of incentives including tax credits and state level mandates such as the Zero Emission Vehicle mandate initiated in California and adopted in some other states. By 2009, there were around 57,185 battery powered vehicles (including neighborhood BEVs) in use in the U.S. excluding demonstration and concept vehicles that were not ready for delivery to end users [29].

Current charging stations for BEVs are primarily located at residences, businesses, public parking lots, and fleet facilities where vehicles may be parked for long periods each day. Even with current fast charging stations, BEVs cannot be recharged in minutes, due to required high power and heat management constraints on the battery side. Table 2.1 presents the charging times for the Nissan Leaf (a commercially available BEV) and Chevrolet Volt (a commercially available PHEV). With current charging station and BEV technologies, long charging time may add constraints on the availability of BEV recharging parking space, and may still be a concern from the perspective of consumer acceptance. [30]

Table 2.1

Example charging times for different vehicle batteries and voltages

(modified from: [31])

Vehicle model	EPA-estimated EV range, miles	Battery Capacity	Hours to fully charge empty battery	
			Level 1 (110/120 V)	Level 2 (220/240 V)
Nissan Leaf	100	24 kWh	20	7
Chevrolet Volt	35	16 kWh	10	4

The limited charging rate, long charging time, along with the charging equipment requirements, and other charging characteristics (such as the fact that BEVs can be plugged into an electrical outlet) make home refueling a natural fit to BEVs, if designated parking space is available at home. Drivers need to charge their vehicles where they park their vehicles for long periods each day, and home is most often a convenient place. A study by Axsen and Kurani found that slightly more than half of American households buying new cars has the potential to recharge a vehicle at home with at least 110-V service, and few drivers perceived an opportunity for non-home recharging opportunities, such as at their workplace, friends' and family's homes, and restaurants [32].

Additionally, some electric utilities have offered time-of-day rates to BEV customers for charging their cars at night when electricity demand is typically at its lowest. The lower electricity cost at night makes home refueling more attractive to consumers. Based on consumer surveys and utility observations, 95% of California's current BEV drivers charge at home, mostly overnight [33, 34]. Home refueling appears to be fundamental to BEVs at least for the time being and the foreseeable future before super fast recharging stations become available.

Upgrading of the recharging facility is most likely required in the U.S. (current facility has 110 volt outlets) to meet the recharging needs of BEV drivers, and the cost of the upgrading varies depending on the types of recharging facilities, and various constraints such as the availability of BEV recharging parking space.

The cost for upgrading a residential garage recharging system for single family residences is estimated at $870 - $2,200 [35]. Providing BEV recharging in multifamily residential buildings appears to have more constraints and be more costly. For instance, for multifamily residential buildings without designated parking, extra costs on BEV recharging parking need to be considered. The installation costs of a BEV recharging station can range from $2,000 to $10,000 [31].

In comparison, the capital costs of home refueling equipment for other AFVs such as CNG vehicles and FCVs are reviewed. The cost of a home refueling appliance for CNG vehicles is around $6,000, and the cost for providing a home refueling system for FCVs is projected to be above $10,000 [36, 37]. Cost and other concerns such as perceived safety may have significant impact on consumers' purchasing decisions, which may make the marketing strategies fundamentally different between BEVs (and PHEVs) and other AFVs of interest.

2.2.4 Home Refueling for Plug-in Hybrid Vehicles

With a few companies announcing their production plans in the coming years, PHEVs have drawn considerable public attention. With existing gasoline stations, fuel availability is not a concern. However, for consumers to be able to drive the vehicle primarily with electricity to realize the multi-faceted benefits of PHEVs, recharging methods matter. Most current PHEV models are designed such that they can be simply plugged into a conventional outlet, although for PHEVs with relatively larger battery capacity the Level 2 charging facility may be preferred or even required to allow drivers to drive the PHEV mostly with electricity. It is expected that home recharging will play a major role for refueling these PHEVs at least in the near term when non-home recharging opportunities are limited [32].

Recharging for PHEVs is similar to BEVs in that conceptually they both can be recharged wherever parking and an electrical supply coincide. However, there can be differences between PHEVs and BEVs depending on the size of the battery in a PHEV. The charger cost can be less for PHEVs than for BEVs, and upgrading of recharging infrastructure may not be required for PHEVs. But an electrical infrastructure upgrade may be required for a PHEV with long charge depleting range (and thus, a large battery) [35].

Similar to the discussion in Section 2.2.3, home recharging is regarded by many as fundamental to PHEVs as well [38-40].

2.2.5 Home Refueling for Fuel Cell Vehicles

Although some companies have made FCVs available to selected consumers through leasing programs, they are not commercially available. The number of FCVs in use in the US was 357 by 2009, excluding demonstration and concept vehicles that are not ready for delivery to end users [29]. While announcing their near term plans for small scale pre-mass production of FCVs, major automobile companies acknowledge there still are barriers on the commercialization of FCVs. Among other barriers, lack of a hydrogen infrastructure system is probably the most daunting.

Convinced that home refueling can help evade the “chicken and egg” infrastructure-vehicle problems, several companies including major automobile and FC system manufacturers are in partnerships to develop and test their home hydrogen refueling outfits to partially solve the fuel availability problem. Current solutions these companies are exploring can be separated into two categories. The first category is an electrolysis unit to split water to hydrogen and oxygen and feed hydrogen to a vehicle. The second category is a small-scale tri-generation system, which can produce electricity, heat, and hot water simultaneously by converting fossil fuels such as NG. Compressors, dispensers, and storage are typically integrated in the system.

Among the aforementioned AFVs, providing home refueling for FCVs seems to be the most challenging. These systems are costly and complex, unless technology advances make low-cost electrolyzers and tri-generation systems available. The tri-generation configuration is designed to improve the economics, giving more motivation to consumers to adopt such systems. First, it spreads out the capital costs among three types of energy needs, electricity, hot water and transportation fuel. Second, the economics of operating the system may be improved by providing the three types of energy products rather than providing only transportation fuel (because electricity and heat is needed on a daily basis, the utilization level is higher), if designed properly. To society, the adoption of these systems may provide wide availability of hydrogen fuel to early consumers with less investment while hydrogen demand is low.

2.3 A Comparison of Home Refueling for Different Types of Vehicles

The history of home refueling for gasoline vehicles still has important implications for home refueling for AFVs. Home refueling for AFVs can alleviate consumer 'concern for fuel availability when easy access to an extensive network of public fueling stations is not available. Home refueling also provides convenience and security of refueling at home. Presently, home refueling is used by some CNG, BEV, and PHEV vehicle drivers. Their preferences and responses to home refueling systems (especially CNG vehicles) provide valuable information for home refueling for other AFVs. There has not been any real world end-user experience of home refueling for FCVs so far, though a number of companies are investing in the research and development of home refueling systems for FCVs. For BEVs, home refueling appears to be essential for basic functionality in addition to other goals and less economically challenging at least for the time being. For PHEVs, home refueling opens up the potential benefits of a dual-fuel vehicle—one fuel available in a large-scale retail network and the other at home and other parking locations (assuming the coincidence of parking and electricity at these places).

A comparison among home refueling systems for different vehicle types is given in Table 2.2 to present the issues faced by various AFVs and facilitate further exploration of the implications.

Table 2.2

Home refueling for different alternative fuel vehicles (in 2008 dollars)

Vehicle type	Equipment	Fueling Time	Equipment cost (installation excluded)	Fuel cost	Consumer experience	Fuel source
Gasoline Vehicle	A pump and a tank	Several minutes	--	\$0.06/kWh ~0.12 kWh (non-home refueling)	Yes (mostly during 1900-1915)[4]	Delivered gasoline
CNG vehicles	A compressor, NG supply, and dispensing equipment	Several minutes ~ several hours (for a full tank for a 300 miles range depending on storage availability)	\$3000 ~ \$4000	\$0.04/kWh ~ \$0.07/kWh (\$1.1/therm ~ \$2.0/therm)	Yes	Existing residential NG

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[4] Note: in table 2.2, home refueling for gasoline vehicles is provided as a reference for home refueling, not as an example, because few, if any, living consumers in the US have experience with gasoline home refueling.

BEVs	An outlet, a charger and grid or stand-alone electricity	Hours (for a full recharging for a 100 miles range)	0 ~ $10,000 [a]	$0.05/kWh ~ $0.15/kWh	Yes	Grid electricity
PHEVs	An outlet, a charger (may be unnecessary for some PHEVs, and grid or stand-alone electricity	Hours (for a full recharging for a 60 miles range)	0 ~ $10,000	$0.05/kWh ~ $0.15/kWh	Yes	Grid electricity
FCVs	An electrolysis unit or a reforming system, energy supply, and dispensing equipment	Several minutes ~ several hours (for a full tank for a 300 miles range depending on storage availability)	$10000 ~ $20000[b]	$ 0.11 kWh ~ $ 0.25 /kWh ($3.5/kg ~ $8/kg) [c]	No	Existing residential NG, or Grid electricity

Note: a, b and c, the prices are estimates based on available literature [35, 36, 41].

2.4 Neighborhood refueling

Neighborhood refueling would provide transportation fuel to residents of a particular neighborhood or community. Neighborhood refueling systems are located near or in a community to offer convenience and security similar to home refueling.

Neighborhood refueling systems may include a dispensing system or an outlet connected to a dedicated facility with support personnel and power distribution infrastructure [42].

Neighborhood refueling is different from home refueling, in that neighborhood refueling outfits are sized for several homes rather than only one. The capacity may be 10 to 20 times larger than home refueling outfits; and the materials, specifications, economies of scale and efficiencies are different. Neighborhood refueling is also different from conventional public refueling stations, which typically can serve hundreds of vehicles per day. First, the capacity of neighborhood refueling is much smaller. Second, neighborhood refueling would be located near or in the community to offer convenience and security similar to home refueling.

The demand for neighborhood refueling is aggregated demand of 10-20 households; the aggregated electricity and hot water demand profiles for neighborhood tri-generation systems are less peaky than that of each individual household, which may improve the economics of the systems. Higher capacity factor and utilization of the neighborhood system can be achieved relative to the home system for each individual household. Neighborhood refueling systems can be operated commercially or as co-ops. One example of neighborhood refueling would be some existing bio-diesel co-ops, where a group of people from a community come together to invest in processing waste vegetable oil into bio-diesel.

Neighborhood refueling systems can be installed outside a residential area, such as at workplaces as well. However, some characteristics of neighborhood refueling should be taken into account when adopting these systems outside a residential area.

1. First, are the demand profiles for hydrogen, heat, and electricity suitable for neighborhood refueling systems in terms of economic benefits? For example, does the electricity demand profile coincide with heat demand profile?
2. Second, does the location of the system offer convenience and security similar to home refueling? This can be measured by the distance from the location people live or work to the refueling systems. Geographic closeness is important to provide the sense of neighborhood or/and community. Other attributes that are difficult to measure such as familiarity and perceived security of surrounding environment are important as well[5].

Neighborhood refueling is suitable for multi-family residences (e.g., townhouses and condominiums); they can serve a community of single family residences as well, as long as it is economical to install and operate these systems, e.g., the electricity demand profile coincides with heat demand profile. Neighborhood refueling may be particularly important for densely populated areas, such as some cities in the east and west coast in the U.S., Europe, and Asia, where individual garages, carports or other reserved parking are not available for home refueling. These areas are most often where criteria pollutants emissions problems are more severe.

2.5 Consumer Preferences and Response

Consumers' preferences, responses and, ultimately, their purchasing decisions are essential to the commercialization of home and neighborhood refueling systems. Before

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[5] One example of neighborhood services or products that can offer some analogy is vending machines for refilling drinking water installed in some communities such as the Orchard Park at UC Davis and some residential areas in Shanghai. The author had personal experience with refilling water using the machines.

making a purchasing decision, consumers evaluate the costs, and the benefits associated with a product or service, these benefits may be functional, psychological, and social. 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 [43]. Marketing organizations need to understand the preference structure of consumers for home and neighborhood refueling systems. Do consumers like refueling at home? What functional and psychological benefits associated with these systems do they value the most? More importantly, how much is the targeted consumers' WTP for these systems?

Some previous research and government documents on home refueling for CNG vehicles and BEVs indicate that consumer response to home refueling is overall positive. As pointed out in [14], refueling at home is an attractive benefit to a large proportion of drivers (57% in their survey), and some studies "consistently find a large proportion of drivers who dislike fueling at retail gasoline service stations, sometimes to the point of consistently requiring a spouse or other person to refuel the vehicle." [14]

Abbanat [11] asked a stated preference question for CNG vehicle drivers to estimate their WTP for a home refueling appliance: the results suggest few were willing to pay over $5,000 for the appliances. Although these studies offer some clue on consumers' overall opinion of home refueling, very few studies focus on understanding the preference structure of consumers for home and neighborhood refueling systems; and the positive consumer response and lessons learned on home refueling for CNG vehicles and BEVs demonstrate its potential and warrant further research.

2.6 Important Questions, Challenges and Opportunities

Home and neighborhood refueling technologies for AFVs are currently available, and no major technological barriers exist to the widespread commercialization of home refueling systems for CNGs, PHEVs or BEVs. Home refueling technologies for FCVs are in an earlier stage of development, and there is much uncertainty in terms of technology improvement and cost reduction. The biggest challenges for providing home refueling service for FCVs are associated with cost and addressing consumers' perceived safety concerns such as fire and/or explosion.

Despite the potential for home and neighborhood refueling to play an important role in attracting consumers to use alternative fuels and partially solving the fuel availability issue, many questions essential for the commercialization of home and neighborhood refueling technologies remain unanswered, including [36]:

1. What are the technical, environmental, and economic performances of the home and neighborhood refueling technologies?
2. What are the constraints on the practical viability of the technologies?
    a. Potential limits on practical viability include local land-use regulations, building codes, and noise standards, the covenants, codes and restrictions (CCRs) of many private communities, and any of a number of other possible limits on home refueling that may not have constrained the role of home refueling for gasoline at the birth of the automobile.
3. How much will consumers value the multi-faceted benefits associated with home and neighborhood refueling?

   a. What is their WTP for the service?
   b. And how will they pay?
   c. How will they value aspects such as loss of space in or near a parking area, noise and vibration, scheduling maintenance of home refueling devices, losses of mobility caused by outages of home refueling systems?
4. How and to what extent will policy impact the commercialization of the technologies? These policies include not only the apparent drivers for clean air, greenhouse gas emissions reductions, energy security, and fuel flexibility, but also contemporary efforts to revive a domestic US automobile industry.
5. Is home and neighborhood refueling a permanent or transitional strategy? And is it likely to be permanent for some “fuels” and transitional for others?

Home refueling with tri-generation systems for FCVs provides home heat and electricity in addition to transportation fuel, and thus better economics than systems that provide only vehicle refueling. Several companies are investing in hydrogen home refueling systems, and some data have become available on their performance and cost. Little research has been done on neighborhood refueling methods. Independent studies to evaluate the technical, environmental, and economical performances of these home and neighborhood refueling systems are needed to better inform policy makers and the public about their potential.

2.7 Chapter Summary

An important analogy from the early development of the gasoline station network is that innovative, small volume, and widely available refueling methods including home and neighborhood refueling may be necessary during the introductory periods of AFVs.

Furthermore, home refueling offers many attractive features other non-station refueling methods and a sparse public station network could not offer including reduced trips to refuel vehicles, convenience, and security of refueling at home. Some previous research and government documents on home refueling for CNG vehicles and BEVs indicate that consumer response is overall positive. A stated preference survey study with CNG vehicle drivers suggests few drivers were willing to pay over $5,000 for the appliances.

Cost and other concerns such as perceived safety may have significant impact on consumers' purchasing decisions, which may make the marketing strategies fundamentally different between BEVs (and PHEVs) and other AFVs of interest such as CNG vehicles and FCVs.

Neighborhood refueling is suitable for multi-family residences (e.g., townhouses and apartment complexes); it can serve a community of single family residences as well, as long as it is economical to install and operate these systems. Neighborhood refueling may be particularly important for densely populated areas where individual garages, carports or other reserved parking are not available for home refueling. These areas are most often where criteria pollutants emissions problems are more severe, and use of zero emission vehicles such as FCVs would help ameliorate these issues.

Chapter 3: Research Questions and Scope

In Section 2.6, a number of questions essential for the commercialization of home and neighborhood refueling technologies are raised for the aforementioned vehicle types. It is beyond the scope of this study to answer all these questions for all vehicle types discussed. I focus on exploring answers to questions 1, 3, 4 listed in Section 2.6. The objectives of this dissertation are to provide analytical tools for various stakeholders such as policy makers, manufacturers, and consumers, to assess home and neighborhood refueling methods for FCVs in a systematic way, and to apply these tools to case studies using real world energy demand data, energy prices and other engineering/ economic inputs. With these case studies we can showcase the capabilities of these analytical tools and better understand the design, and technical, economic, and environmental performances of home and neighborhood refueling for FCVs. The case studies focus on simulation and detailed analyses of home and neighborhood refueling for hydrogen FCVs using tri-generation systems.

Several tasks are carried out to address the main research questions related to home and neighborhood refueling methods for FCVs, and to achieve the research goals.

1. Present a historical review and comparison of home and neighborhood refueling methods for a wide range of motor vehicles and fuels, and to summarize the important questions, challenges, and opportunities of adopting home and neighborhood refueling methods for alternative fuel pathways with emphasis on FCVs. This task is accomplished in Chapter 2.

2. Construct an interdisciplinary framework to analyze home and neighborhood refueling methods by integrating theories from thermodynamic, chemical thermodynamic, engineering economy, consumer behavior research etc. This is presented in Chapter 4.
3. Develop and utilize an engineering/economic model on the basis of the interdisciplinary framework to assess home and neighborhood refueling systems for FCVs. In particular, this study focuses on tri-generation systems that simultaneously produce electricity and heat for residential buildings, as well as hydrogen fuel for vehicles. Tri-generation systems may offer better economic performance than simple hydrogen refueling systems, by displacing costly purchased grid electricity and by improving utilization of hydrogen production equipment. The model is presented and explained in Chapter 4.
4. Quantify consumer's response, preference structure, and willingness to pay for home and neighborhood refueling systems and incorporate them into the modeling process. This topic is discussed in Chapters 4 and 5.
5. Conduct analyses of the environmental impacts (GHG emissions) of home and neighborhood refueling systems. The environmental cost of emissions will be incorporated into the engineering/economic analyses as well. This task is addressed in Chapters 4, 5, and 6.
6. Review relevant existing policies (such as policies associated with home refueling , co-generation, renewable energy, alternative fuels, etc.).The policy implications of the engineering/economic analyses will be explored to inform various stakeholders such as policymakers, automobile companies, and FC

system manufacturers. This topic is discussed mostly through the case studies in chapters 5 and 6.

Chapter 4: Methodology

4.1 Tri-generation system description

Tri-generation systems are designed to meet the three energy needs of a typical household: electricity, heat, and transportation fuel. In the U.S. these three energy needs are typically met by grid electricity, NG heat (some places also use electricity or oil for heating), and gasoline. A tri-generation system produces electricity and heat for buildings as well as hydrogen fuel for vehicles by converting a hydrocarbon such as NG or biogas.

A typical configuration of a tri-generation system is shown in Figure 4.1. The complex system can be regarded as consisting of six major components: a fuel reformer, a water-gas shift (WGS) processor, a purifier, a compressor sub-system, a storage sub-system (depending on system configurations and refueling pattern assumptions), and a FC sub-system. The mechanism of how the system works is as follows.

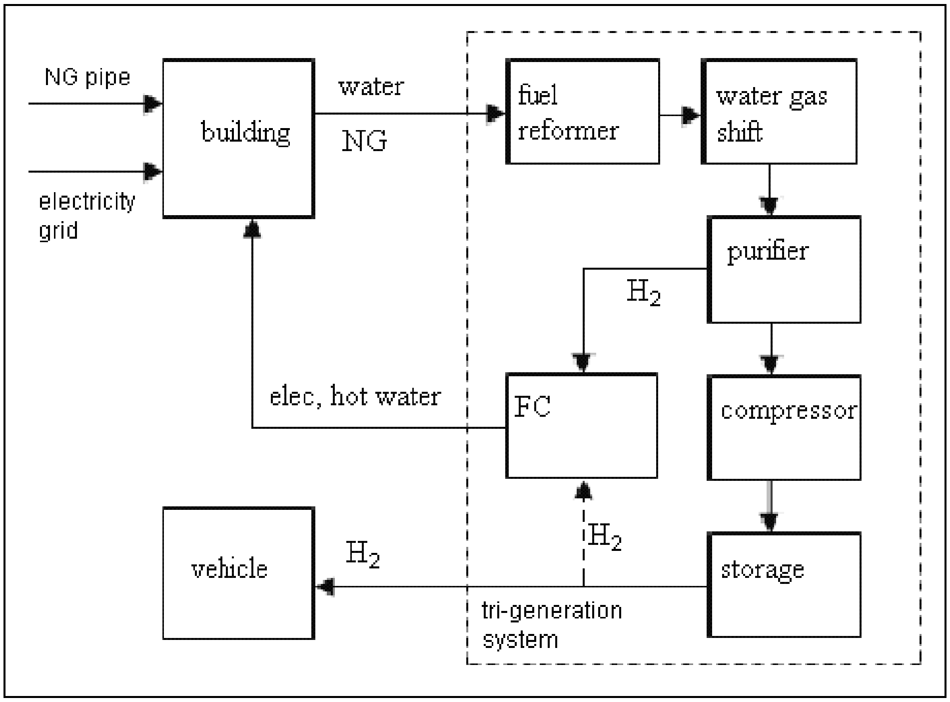

Fig. 4.1 The schematic of a typical tri-generation system (source: [18])

The Fuel Reforming Process

A fuel reformer converts NG or other hydrocarbons to a mixture of hydrogen and other gases such as CO and CO_2. The fuel reformer modeled in this study is an autothermal reformer (ATR); other reforming technology such as steam reforming can also be used. The ATR reforming of NG converts a mixture of steam, NG and the oxygen in the air to H_2 and other gases such as CO and CO_2. It combines several reactions including steam reforming, partial oxidation, and water gas shift. Because the heat released by the exothermic reactions such as partial oxidation reaction is used by endothermic reforming reactions (e.g., steam reforming), no external heat is theoretically required for the reforming process. A catalyst is normally needed to accelerate the reactions. The main reaction formulas during the ATR reforming process of NG include the following: [44]

$CH_4 + H_2O \rightarrow CO + 3H_2$ $\Delta H = +206$ kJ/mol, steam reforming reaction

$CH_4 + 2\,(O_2 + 3.76\,N_2) \rightarrow CO_2 + 2\,H_2O + 7.52\,N_2$ $\Delta H = -802$ kJ/mol, full oxidation reaction

$CO + H_2O \rightarrow CO_2 + H_2$ $\Delta H = -41$ kJ/mol, water gas shift reaction

$2CH_4 + (O_2 + 3.76\,N_2) \rightarrow 2CO + 4H_2 + 3.76\,N_2$ $\Delta H = -247$ kJ/mol, partial oxidation reaction

Where,

ΔH is the reaction enthalpy; and reactions are assumed to take place under the condition of 1 atm and 25 ^{o}C.

Reforming efficiency η_{reform} is defined as in Equation 4.1 [44]. η_{reform} is a very important parameter for later analysis, since the reforming process is a major contributor to efficiency loss, which determines the economics of tri-generation systems.

$$\eta_{\text{reform}} = (n_{H2} + n_{CO}) * (\text{LHV of } H_2) \,/\, [n_{NG} * (\text{LHV of NG})] \qquad (4.1)$$

Where,

n_{H2}, n_{CO}, and n_{NG} are the amounts of molecules of H_2, CO, and NG, respectively;

LHV stands for lower heating value.

Because most CO generated in the reforming process can be converted to H_2 later in the water gas shift reactor with the addition of water, n_{CO} appears in Equation 4.1 as well [44].

The ATR reforming process can be modeled by using an equilibrium calculation with some parameters adjusted based on empirical data.

The Water-Gas Shift (WGS) Process

A WGS processor further converts most of the CO to hydrogen and CO_2. The WGS reaction is a process in which CO reacts with water to form CO_2 and H_2.

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H = -41 \text{ kJ/mol, WGS reaction}$$

This reaction is widely used as a CO removal method for the reformate from a reformer. The WGS reactor efficiency η_{WGS} can be defined as in Equation 4.2.

$$\eta_{WGS} = n_{H2} * (\text{LHV of } H_2) / n_{CO} * (\text{LHV of CO}) \qquad (4.2)$$

Similar to modeling the ATR reforming process, WGS reaction can be modeled based on an equilibrium calculation.

The Reformate Purification Process

Pressure swing adsorption (PSA), selective permeation using membranes, and cryogenic separation are three main hydrogen purification technologies used in refineries. The three technologies are based on different separation principles, and have different characteristics. Table 4.1 summarizes the characteristics of the three hydrogen purification technologies. [45]

Table 4.1

Characteristics of the three hydrogen purification technologies (source: [45])

Characteristics	PSA	Membrane selective permeation	Cryogenic separation
Good feed H_2 by vol., %	50	15%	15%
Feed pressure, psi	150 - 1,000	200 - 2,000	200 - 1,200
H_2 Purity, %	≥ 99.9	≤ 98	≤ 97
H_2 Recovery, %	up to 90	up to 97	Up to 98
CO & CO_2 Removal	Yes	No	No
H_2 Product pressure	Approximately feed pressure	Much less than feed pressure	Approximately feed pressure
Feed treatment	No	Yes	Yes
Flexibility	Very high	High	Average
By-product recovery	No	Possible	Yes
Ease of expansion	Average	High	Low
Applicable at home or neighborhood scale	Yes	Yes	No

A PSA purifier is considered in this study for separating hydrogen from other impurities to produce hydrogen with high purity, normally greater than 99.9%. High purity hydrogen is required to avoid poisoning the PEM FC system in a FC car or within a tri-generation system [46]. In a PSA purifier, special adsorptive materials (e.g., activated carbon or zeolites) are used as adsorbents, preferentially adsorbing the impurities at high pressure. Hydrogen is not adsorbed. The process then swings to low pressure to release the impurities. The PSA units are suitable to be used in a tri-generation system, in that they are able to remove impurity to a very low level and achieve a high-purity, high-pressure hydrogen product. The typical pressure drop between feed and product gases is less than 10 psi, and some recompression duties are avoided [45]. Additionally, PSA units are widely used in industry and are economical to use.

We note that liquid hydrogen purification (cryogenic separation) requires very large size because of economies of scale (as in a refinery), and is not suitable for home or neighborhood scale hydrogen production. Membrane separation is feasible at small scale, and is more costly than PSA systems.

The H_2 Compression Process

In this dissertation hydrogen is stored on-board a vehicle, and the storage unit within a tri-generation system (if there is one) as high pressure (5,000 psi) compressed gaseous hydrogen (CGH) to achieve high energy density (2.75 MJ liter $^{-1}$, at ambient temperature). Compression of the hydrogen consumes a large amount of electrical energy, normally ranging from 6%-12% of the hydrogen energy content contained in the hydrogen storage unit. As shown in Equation 4.3, the efficiency of the compression η_T can be formulated as the product of the isentropic efficiency η_c and the mechanical efficiency η_m. [46]

$$\eta_T = \eta_c * \eta_m \tag{4.3}$$

The isentropic efficiency is the ratio of the isentropic work and the actual work. Here, the actual work is the work done to raise the pressure from P_1 to P_2 without considering mechanical energy losses on the shaft used to drive the compressor. When the pressure of the gas changes from P_1 to P_2, the temperature of the gas will change from T_1 to T_2. The isentropic work is the work that would have been done if the compression process were reversible.

Based on the thermodynamic basics, η_c can be calculated with Equation 4.4.

$$\eta_c = \frac{T_1}{T_2 - T_1} \left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} -1\right) \tag{4.4}$$

With a simple manipulation of Equation 4.4, the temperature change of the compression process can be calculated with Equation 4.5.

$$\Delta T = T_2 - T_1 = \frac{T_1}{\eta_c} \left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} -1\right) \tag{4.5}$$

The power needed to drive the compressor can then be calculated using Equation 4.6 or 4.7.

$$\text{Power} = \dot{W} = c_p * \Delta T * \dot{m} \qquad (4.6)$$

$$\text{Power} = c_p * \frac{T_1}{\eta_c} \left(\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} -1 \right) * \dot{m} \qquad (4.7)$$

In reality, there is mechanical energy loss on the shaft used to drive the compressor, so the calculated power so far needs to be divided by η_{m} to obtain the actual power needed. [46]

H2 Storage

It is assumed that certain amount of hydrogen are stored at the home and neighborhood refueling sites to accommodate fast refueling of an FCV. The hydrogen stored is enough to refuel one car for a home system, and 10-20 vehicles for a neighborhood system; details on how the amount is determined will be given later in case studies (Chapters 5 and 6). The hydrogen stored serves two purposes. First, it enables fast refueling of vehicles; second, it can facilitate fast start-up and transients of the tri-generation system. Storing hydrogen as CGH is currently the most technically straightforward and most widely used method for small amounts of usage, and is considered in this study [46]. Because it is stationary storage of hydrogen, the energy loss is mainly the loss of hydrogen due to leakage and venting. The loss of hydrogen during extended residence time is typically normalized to the mass of hydrogen stored with a unit of "(g h^{-1})/ (kg H_2 stored)". The Department of Energy (DOE) target for the loss of hydrogen from a storage tank for 2010 is 0.1 (g h^{-1})/ (kg H_2 stored) for safety reasons, which exceeds the requirement of applicable safety standards [47]. For a 5 kg cylinder, the loss of hydrogen during a year can be calculated as in Equation 4.8.

$$8760 \text{ h} * 0.1(\text{g h}^{-1})/(\text{kg H}_2 \text{ stored}) * 5 \text{ kg H}_2 \text{ stored} = 4.38 \text{ kg} \qquad (4.8)$$

We can also put this in terms of average usage of H_2 per day by a passenger car (about 0.7 kg, based on 15,000 miles driven annually), and thus:

$$24 \text{ h} * 0.1(\text{g h}^{-1})/(\text{kg H}_2 \text{ stored}) * 5 \text{ kg H}_2 \text{ stored} = 12 \text{ g d}^{-1}$$

The loss of hydrogen in both calculations accounts for around 2% of hydrogen fuel that a typical passenger vehicle would consume in the US, and has a small impact on the economic performance of operating the tri-generation system. It is worth noting that loss of hydrogen from a storage system is both a safety and cost issue. In this dissertation we are only concerned with the cost[6].

The FC Sub-system and Energy Products

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[6] The cost of addressing the safety issue is embedded in the price of the storage system. As long as the system meets the safety standards and is allowed to be on sale, the loss of hydrogen will be less than what we assume in this dissertation.

The high purity hydrogen produced can be used by a FC sub-system to generate electricity. The net DC power to hydrogen efficiency curve of a PEM FC sub-system is shown in Figure 4.2. During the electricity generation process heat is generated as a by-product and can be captured for hot water heating and space heating. Part of hydrogen produced can be compressed and used to refuel a FC car. Certain amount of hydrogen can also be compressed and stored to allow fast refueling of the FC car depending on the system's operational strategy and configuration. With fast refueling, vehicles can be refueled to a full tank within several minutes (approximately 1 kg of hydrogen per minute. [6] Fast refueling normally requires hydrogen stored on-site. Home system can be designed with slow refueling or fast refueling. Neighborhood system needs to be designed with fast refueling, since the refueling site is not intended for long time parking and consumers need to share one dispenser.

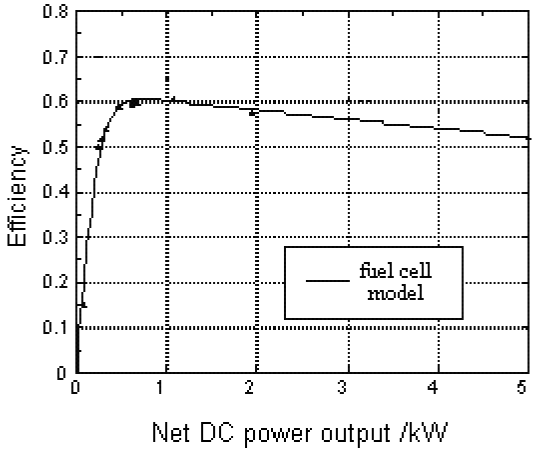

Fig. 4.2 Net DC power to hydrogen efficiency of the FC sub-system
(modified from: [17])

<u>The Operational Strategies of a Tri-generation System</u>

Operational strategies of a tri-generation system can significantly affect the design and economics of installing and operating the system. We considered a number of potential strategies that define how tri-generation systems could operate, described below. Other strategies are possible as well.

1. Stand alone vs. grid-connected. Stand alone system is not connected with the electricity grid. All energy needs are satisfied with the system and NG supply. A grid-connected system is able to buy or sell electricity from and to the grid when it is more economical to do so. More details on selling and buying electricity is provided in section 4.3.1.
2. Heat vs. electricity load following. For heat load following strategy, the system operates to follow the heat load, and electricity is the by-product of the heat generation process. For electricity load following, the system operates to follow the electricity load, and heat is the by-product of the electricity generation process.
3. 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 customers to refuel to a full tank whenever they want within a few minutes. Certain amount of hydrogen storage is provided; more details are given in case studies (Chapters 5 and 6).

Operational strategies can significantly impact 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.

4.2 The Interdisciplinary Analytic Framework for Tri-Generation Systems

In this study, an interdisciplinary framework is developed to analyze tri-generation systems in a systematic way. 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, engineering economy, and consumer behavior research, and is illustrated in Figure 4.3.

The framework consists of two main stages: first, the engineering modeling of hydrogen production, and electricity and heat generation in a fuel cell; 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 to generate the efficiencies of the components of the tri-generation system. In the second stage, engineering economic analyses are conducted on the basis of the engineering performance inputs from the first stage, cost data, and other economic inputs; consumer preference (represented as consumer's WTP in the model) and environmental cost information is integrated into the modeling process as well. More details on consumer preference and environmental cost are provided in Section 4.3. The last arrow highlights the outputs of the analyses.

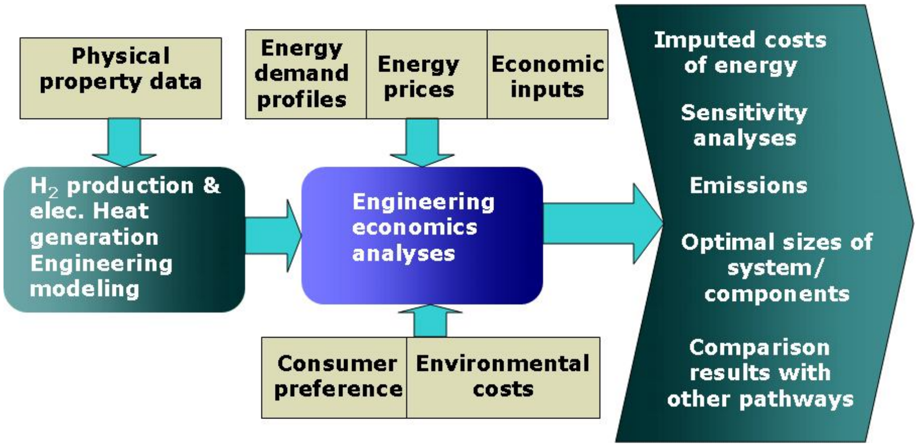

Fig. 4.3 Interdisciplinary framework for analyzing tri-generation systems

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 (defined as the size that allows a tri-generation system to meet the three energy needs with minimal life cycle cost from a consumer's perspective) of a system or components are also of interest to manufacturers and consumers. It is worth noting that model results vary with data inputs and main assumptions. Table 4.2 presents a summary of main data sets and assumptions in this dissertation. More details on data and assumptions can be found in later chapters on case studies (Chapters 5 and 6). 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.

Table 4.2

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 for home refueling case studies, and employ data for a representative multi-family residence in Sacramento area for neighborhood refueling case studies. The electricity demand profiles are provided by California Energy Commission. Other energy demand data are gathered from EIA data and the literature [48].
Energy price data	Historical data are used for NG, electricity and gasoline prices in the Sacramento area. Projected near-term hydrogen prices are from conceptual design studies by other researchers [5].
Capital Cost assumptions	The manufacturing cost of main components of tri-generation systems (e.g., fuel reformer, FC system, and dispensing system) varies significantly with different levels of production volume. We choose to use a bottom-up mass production cost assessment in this study [37]. 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* = 0.149.

4.3 The HTS (H_2 tri-generation system) Model

An engineering/economic model for hydrogen tri-generation systems (the HTS 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 [49]. As shown in Figure 4.1, there are six 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. Each component is modeled based on thermodynamics and other relevant engineering theories as described in Section 4.1, and the efficiency of each component can be calculated. The efficiency of the entire system is the product of the efficiencies of all five components. Table 4.3 presents main efficiency and other engineering parameters, which 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 given yearly energy demand profiles of electricity, heat, and transportation fuel. The NG input is a major component of variable operation cost.

Table 4.3

Main engineering parameters

Reformer efficiency [17]	75% (this parameter represents the combined efficiency of fuel reformer, water gas shift processor, and purifier in Figure 4.1)
FC stack efficiency η_{FC}, (also shown in Figure 3) [17, 46, 50]	$\eta_{FC} = \{1\text{-}\exp[-0.5(P/P_{FC,max})^{1.2}]\} \ast[0.622-0.002(P/P_{FC,max})]$, 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 [17])
Compressor efficiency [51]	80%
Parasitic load efficiency, the percentage of generated electricity used for parasitic load [46]	15%
AC/DC power conversion efficiency [17]	92%
H_2 Utilization in Fuel Cell [17]	85%
Hot water tank efficiency (NG to hot water heat) [17]	75%
Rate of heat (by product of electricity generation) captured for hot water [17]	70%

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

1. How much does it cost to install and operate home and neighborhood tri-generation systems? When does it make economic sense for the consumer to install a particular system compared to alternatives?
2. How do energy demand profiles (for hydrogen, electricity, and heat) influence system design?
3. What role can system capital cost financing arrangements (versus upfront system purchase) play in the commercialization of these technologies?
4. 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?
5. How can environmental costs be considered and included in the analyses? How does the cost of energy products produced by tri-generation systems compare to alternatives?
6. Consumers' preferences, responses (such as positive reviews and comments), and purchase decisions on vehicles and refueling services are essential to the commercialization of home and neighborhood refueling systems. Before making a purchasing decision, consumers evaluate the costs, and the benefits associated with a product or service, these benefits may be functional, psychological, and social. If the price of a product or service is above his/her WTP, a consumer will not purchase the product or service [43]. 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?

4.3.1 The Engineering/Economic Analysis Approach

With a tri-generation system there are three energy products: electricity, heat, and hydrogen fuel, which complicates the engineering/economic analysis. One engineering/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 fuel from a public station depending on the types of vehicles). 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 systems .

Another approach is to estimate the levelized cost of one energy product (e.g., electricity) while calculating the value of other energy products (hot water heat, and gasoline or hydrogen) based on market price. During the lifetime 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 lifetime 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. Similarly, levelized cost of hydrogen can be calculated by incorporating the value of electricity and hot water heat based on market price.

In this study the levelized cost of energy products approach is adopted, and main equations for this approach are explained as follows. As shown in Equation 4.9, all annual tri-generation system costs are quantified at the right hand side of Equation 4.9.

$$C_{\mathrm{elec}} = CRF \times CC + CC_{\mathrm{o\&m}} - Cr \qquad (4.9)$$

Where,

C_{elec} is annual cost of electricity (\$ y^{-1});

CRF is capital recovery factor;

CC is present value of life cycle capital cost of a system (\$);

$CC_{\mathrm{o\&m}}$ is annual operating and maintenance cost (\$ y^{-1});

Cr is annual credit for heat and transportation fuel (can be either gasoline or hydrogen), since these energy products are provided by the tri-generation system, instead of being purchased from the utility companies and public refueling stations (\$ y^{-1}).

Equation 4.9 can be written as Equation 4.10.

$$C_{\mathrm{elec}} = \overline{R}_{\mathrm{elec}} \times \int P\mathrm{d}t = CRF \times CC + c_{\mathrm{o\&m}} + cv_{\mathrm{o\&m}} - Cr \qquad (4.10)$$

Where,

$\overline{R}_{\mathrm{elec}}$ is the LEC (\$ kWh^{-1});

P is the hourly average electricity demand load (kW), and $\int P\mathrm{d}t$ is annual electricity demand (kWh y $^{-1}$);

$c_{\mathrm{o\&m}}$ is fixed annual operating and maintenance cost (independent of the amount of energy produced) including labor, maintenance costs, and overhead (\$ y $^{-1}$);

$cv_{\mathrm{o\&m}}$ is variable annual operating and maintenance cost (which depends on the amount of energy produced) including feedstock, water, and chemicals (\$ y $^{-1}$).

Equation 4.11 can be derived based on Equation 4.10.

$$\overline{R}_{\mathrm{elec}} \times \int P\mathrm{d}t$$

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

$\theta_1 = P$, $P < 1/5\ P_{\mathrm{FC,\ max}}$ (turn down ratio[7] 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. (4.11)

Where,

C_{WTP} represents consumer's willingness to pay for home and neighborhood refueling service (\$), this variable can be other type of credits as well such as feebates and tax incentives;

n_{NG} is the annual amount of NG consumed (GJ y $^{-1}$);

R_{NG}, is the price of NG (\$ GJ^{-1});

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[7] Turndown ratio is the ratio of minimum capacity to full capacity of the FC sub-system.

R_{elec} is the electricity price (\$ 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 (\$ 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 (\$ y^{-1});

t_{carbon} represents a carbon tax (\$ y^{-1}).

As can be seen in Equation 4.11, the system 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 efficiency and thus 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 with grid electricity. At very low partial load ($P < 1/5\ P_{\mathrm{FC,max}}$) the efficiencies of the FC sub-system and the entire system are relatively low, and purchasing power from the grid may offer better economics. In Equation 4.11 the first integral $\int R_{\mathrm{ele}}\theta_1(P)\mathrm{d}t$ represents purchased power from the grid when the electricity load is lower than $1/5P_{\mathrm{FC,max}}$ (based on a turn down ratio of 5, the FC sub-system is shut down when this is the case). Also, the system allows purchasing electricity from the grid when the electricity load exceeds the capacity of the system ($P > P_{\mathrm{FC,max}}$). The second integral $\int R_{\mathrm{ele}}\theta_2(P)\mathrm{d}t$ in Equation 4.11 represents purchased power from the grid when the electricity load is higher than $P_{\mathrm{FC,max}}$ and the FC sub-system is operating at its maximum 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 lifecycle of a tri-generation system, not only costs but also energy savings incur 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, the efficiency of hot water system, and NG price. $c_{transport}$ 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 conventional system of purchasing grid electricity, NG heat, and gasoline. The annual carbon cost t_{carbon}, in equation 4.11 can be calculated by multiplying the unit carbon tax with the CO_2 emission reduction/increase. The environmental cost of CO_2 emission is then included in the economic analysis, and the environmental cost of other emissions such as CO and particulate matter (PM) can similarly be included as well .

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. Stated preference survey is a survey-based economic technique for estimating the value of non-market products or services [52]. In a revealed preference approach, it is assumed that the preferences of consumers can be revealed by their purchasing behavior [52]. Although there is no market for FCV home refueling systems, the consumers’ preference, response and purchase decisions on home refueling for CNG vehicles and BEVs can provide some data for a revealed preference analysis or estimation in this study.

Because of the resource constraints, a comprehensive stated preference analysis requiring new surveys is beyond the scope of this study. Alternatively, we adopted a revealed preference approach. Specifically, we reviewed previous research and documents on consumer preferences on home recharging for BEVs as well as home refueling for CNG 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 Equation 4.11 [11, 14, 53].

Equation 4.12 is derived from Equation 4.11 after simple manipulation, and is the key equation used to calculate the LEC for a particular tri-generation system configuration.

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

(4.12)

After estimating the LEC, the LEC is compared to the price of grid electricity, as a metric for when the tri-generation system is competitive with alternatives such as the conventional system of purchasing grid electricity, NG hot water heat, and gasoline[8].

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[8] Note: The difference in gasoline and FC vehicles costs are not considered in this analysis.

An analogous equation can be developed for estimating the levelized cost of other energy products such as hydrogen. Equation 4.13 is developed on the basis of Equation 4.12, and is the key equation used to calculate the levelized cost of hydrogen for a particular tri-generation system configuration.

$$\overline{R}_{H2} =$$

$$= [CRF \times (CC\text{-}C_{\mathrm{WTP}}) + c_{\mathrm{o\&m}} + R_{\mathrm{NG}} \times n_{\mathrm{NG}} + \int R_{\mathrm{ele}}\theta_1(P)\mathrm{d}t + \int R_{\mathrm{ele}}\theta_2(P)\mathrm{d}t - R_{\mathrm{elec}} \times \int P\mathrm{d}t -$$

$$c_{\mathrm{heat}} - t_{\mathrm{carbon}}\,] \,/\, D_{\mathrm{H_2}} \qquad (4.13)$$

Where,

$\overline{R}_{H2}$ is the levelized cost of hydrogen;

$D_{\mathrm{H_2}}$ is the annual demand of hydrogen fuel for an FCV.

The levelized cost of hydrogen can be compared with the price of purchasing hydrogen from a public refueling station, as a metric for when the tri-generation system is economically competitive with the system of purchasing grid electricity, NG hot water heat, and hydrogen from a public refueling station for an FCV.

4.3.2 Exploring the Optimal Design of a Tri-generation System

One essential task of exploring the optimal design of a tri-generation system is to determine the optimal size of each component such as the fuel reformer, FC sub-system and parasitic electronic components. The optimal sizes of a tri-generation system allows the system to meet the three energy needs (electricity, hot water heat, and transportation fuel) in a particular household with minimal lifecycle capital and operating cost, given certain energy prices and other engineering/economic inputs.

However, the fact that tri-generation systems are designed to accommodate the three different energy needs makes determining the optimal size of a system complex and difficult. This is particularly true when the refueling pattern of drivers, e.g., when, how often, and how much drivers refuel is highly variable. In this study, assumptions on transportation refueling patterns such as whether to adopt overnight slow refueling or fast refueling patterns are made before analyses.

Frequently there are tradeoffs in determining the optimal sizes of a tri-generation system. For example, the selection of sizes of the reformer, FC sub-system and the parasitic electronic components is a tradeoff between various capital and operation costs, and energy cost savings. These tradeoffs vary significantly with economic inputs and operational strategies as well. The optimal sizes of a load following tri-generation system would differ significantly from a heat following system.

Given energy demand data, energy prices, relevant engineering and economic inputs, and assumptions on hydrogen refueling patterns, the optimal size of a tri-generation is ultimately determined by identifying the optimal size of the FC sub-system. Once we determine the optimal size of the FC sub-system, the optimal size of other system components can be determined.

A “brute force” exhaustive search algorithm is used to identify the optimal size of the FC sub-system and other component sizes. With the brute force algorithm, the optimal solution is generated by systematically enumerating all possible candidate solutions in a search space. In practice, a reduced space is often used with some analyzing to reduce computation cost [54].

In this study, the search space is the range of the electricity demand profile. For example, if the demand profile of a household ranges from 0.5 kW to 5 kW over the entire year, with a 0.1 kW increment in FC sub-system size, there will be 45 possibilities in the search space. The hourly energy use, energy production, and thus annual energy use and production associated with each of the 45 possibilities (or each of the 45 possible FC-sub system sizes) can be calculated. The levelized costs of energy products associated with each possibility (each FC sub-system size) can be determined subsequently. The optimal system size can then be identified, which is the one with minimum cost.

4.3.3 Software Tools Used for Model Development

The HTS model is developed with the Microsoft Excel software tool and the Visual Basic coding program. The Excel software was chosen because of several of its features including user friendly interface and wide availability. With a typical PC, the simulation results for identifying the optimal system sizes can be generated with different time periods ranging from hours to a couple of days, depending on the accuracy requirement, calculation step, and the PC capabilities.

Chapter 5: Home Refueling Case Studies for Single-family Residences

5.1 Energy Demand Data and Key Engineering/economic Inputs

In Chapter 5, home refueling tri-generation systems for single family residences are evaluated. A home refueling tri-generation system can be similar in size to a typical home washing machine. The system can be installed in a garage or outside a house. Because tri-generation systems are designed to provide electricity, hot water, and hydrogen transportation fuel to a residence, it is desirable for us who conduct the analyses such as in this dissertation to have the electricity demand profile, hot water demand profile and transportation fuel consumption data with appropriate time resolution (hour by hour in this study) for a representative single family residence in the region under study.

However, in reality it is difficult to acquire all of these three sets of data. For one thing, no real representative single family residence exists in a region in the U.S. The residential energy consumption varies with income, number of people, and other characteristics of a household. For another, agencies that generate energy consumption data are normally concerned with aggregated data either for communities or for the entire service area. Therefore, except for electricity, very few agencies monitor hour by hour hot water and NG consumption data at a household level. Even for electricity, it is not easy to get hour by hour demand profiles. With the development in smart grids, in the future this type of data may be more readily available. Additionally, the refueling pattern, e.g., when, how often, and how much drivers refuel, of a passenger vehicle is variable, and estimation and assumptions have to be made on the best available data for transportation demand profile.

In this chapter, we employ hourly electricity demand profiles for a representative single family residence in northern California Sacramento area, provided by California Energy Commission [55]. Figure 5.1 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 although the maximum electricity demand reaches 4.47 kW.

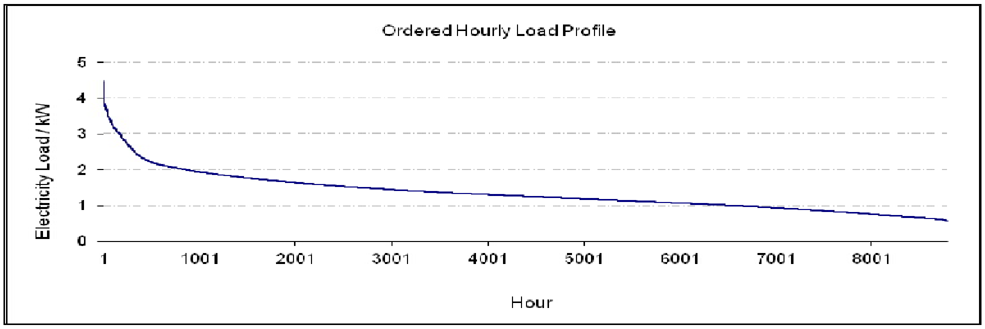

Fig. 5.1 Ordered annual hourly (8,784 hours) electricity load profile

A hot water heat demand profile for the whole year (there are 8,784 hours in the year 2008) is not available, because very few agencies, if any, monitor hot water heat demand at household level. In this chapter, a 24-hour hot water heat demand profile derived from [16, 56] 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. The main reasons are summarized as follows.

First, for a typical residence in a particular region, daily hot water usage such as shower, dish washing, and laundry is fairly constant. The temperature of delivered water does vary with seasons, but most water pipelines are either underground or provided with insulation, which decreases temperature variation in delivered water. Second, based on the energy data shown in Figure 5.2 and Table 5.1, for a typical residence in the region under study the annual total electricity consumption is approximately double the annual total hot water energy consumption, and the distribution and two peaks of the electricity hourly profile coincide with that of the hot water profile well. 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 [17]. Figure 5.2 shows the 24-hour electricity and hot water heat demand profiles of a particular day (January 1, 2008) as an example. Third, the hot water storage tank currently available in residences can act as a buffer and accommodate the small mismatch in electricity and hot water demand.

Space heating energy demand is not considered in this study for a few reasons. First, the distribution, peaks and magnitude of space heating energy demand 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. Second, the time of use rate of grid electricity during night time is normally low, it is not economical to sell electricity back to the grid by operating the tri-generation system to follow the space heating energy demand. As a results, less co-generation benefits can be captured.

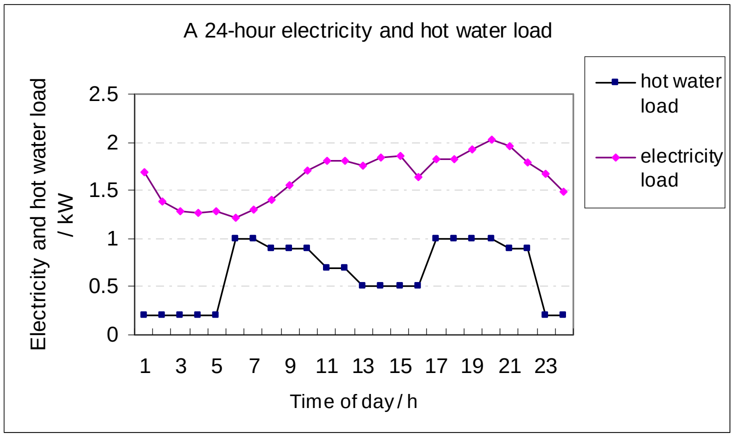

Fig. 5.2 Hourly electricity and hot water demand profile (source: [16, 56])

As shown in Table 5.1, annual total transportation energy consumption is almost twice as large as the annual electricity energy consumption [57], assuming that a passenger vehicle in the residence is driven 15,000 miles each year[9] and the vehicle is a conventional gasoline vehicle with a fuel economy of 25 mpg. If instead we assume the household vehicle is an FCV with a fuel economy of 55 miles per kg of H_2, the annual total transportation energy consumption is approximately as large as the annual electricity consumption. Because the refueling pattern of a passenger vehicle is variable, it is not very meaningful to have hourly transportation demand profile. For the purposes of this dissertation, I only need to know when vehicles arrive at the tri-generation system site and how much hydrogen they draw from the system. Therefore, it is necessary to make estimation and assumptions based on the best available data for transportation demand profile. Section 5.2 presents details on the assumptions on refueling patterns and transportation demand profile.

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[9] Some studies [58] find that on average people in multi-family residences drive less compared with people in single family residences due to issues such as transportation cost burden and land use density. Therefore, we use lower annual miles driven range found in the literature [59]. Based on Energy Information Administration (EIA) statistics, on average a passenger vehicle in the U.S. is driven 12,000 miles annually. I assume a passenger vehicle for a single family residence is driven 3000 miles more than the average, and a passenger vehicle for a multi-family residence is driven 2000 miles less than the average.

Table 5.1 summarizes the annual consumption of the three energy products.

Table 5.1

Summary of the annual energy demand (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

In addition to energy consumption data, model results in this study vary with a number of engineering/economic inputs including efficiencies of energy conversion processes, the prices of energy (grid electricity price, NG price, and transportation fuel price), and various capital, operating and maintenance costs. Table 5.2 shows some of the key engineering/economic inputs used in this study besides the inputs in Tables 4.2 and 4.3. Table 5.3 presents details on how system component costs are estimated.

Table 5.2

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

Price of energy	Based on the PG & E[10] (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 [48].
Cost assumptions	The capital cost of a system is the sum of component costs. The FC stack needs to be replaced every 5 years, and the replacement cost is incorporated into the capital cost.

Table 5.3

Assumptions on system component costs (in 2008 dollars)

Component	Cost
NG reformer [37]	4,616+ 129 $P_{\text{ref,max}}$, ($P_{\text{ref,max}}$ is the capacity of the reformer in kW)
PEM FC system cost [37]	FC stack: 1.1 * {[(454.45 - 105.4) / 10 + 17.56 * 0.6] * $P_{\text{FC,max}}$ * $(1 + 0.06)^5$ / 0.6 + 428.5}, ($P_{\text{FC,max}}$ is the capacity of the FC stack in kW); Ancillary components: 2,980.2 + 35.654 * $P_{\text{FC,max}}$ – 0.0422 * $P_{\text{FC,max}}^2$; Inverter/controller: 542 + 169 $P_{\text{FC,max}}$
Storage System [37]	284 N_t + 192H_{store} (N_t - the number of tanks in the cascade filling storage system, H_{store} - hydrogen stored, kg of hydrogen)
Compressor [37]	1,849.324+116.86 P_{comp}, (P_{comp} is the capacity of the compressor in kg h-1)
Dispenser [37]	371.705+34.547*$P_{\text{ref,max}}$ (for overnight, slow-fill); 474.471+44.098* P_{refmax} (for flexible fast-fill)
Hot water tank [37]	0 (this is necessary for the conventional NG heating system, and the cost is canceled out)

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[10] Note: The electricity demand profile is SMUD (another utility company in Northern California) electricity data provided by CA energy commission, and the electricity price is from PG&E. Both SMUD and PG&E cover some areas of Northern CA, and I assume the time-of –day rate structures from the two companies are not significantly different.

Non-equipment (delivery and installation) [37]	5.7% of equipment capital

Note: The cost estimation is based on a 10,000 units cumulative production volume [37].

It is worthwhile to point out again that the manufacturing cost of PEMFC systems varies significantly with different levels of production volume. Currently, a competitive market for FC systems is not well developed and FC systems are not mass produced. The current market price does not reflect the volume production manufacturing cost because it is for highly customized systems; the current market price is different from the costs in this study and cannot be used. I choose to use a bottom-up mass production cost assessment in this study [37]. 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 and rent for lands can be significantly reduced compared with current practice in installing public hydrogen refueling stations.

5.2 The Optimal Size of a Home Tri-Generation System

As described in Section 4.3.2, the optimal size of a tri-generation system allows the system to meet the three energy needs in a household (electricity, hot water heat, and transportation fuel) with minimal cost, given energy prices and other engineering/ economic inputs. However, the fact that tri-generation systems are designed to accommodate three different energy needs makes determining the optimal size of a system complex, and the fact that we do not have actual data on refueling pattern, i.e., when drivers arrive at the refueling site and how much fuel they draw from the facility is highly variable, makes it even more difficult.

For single-family residences, 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. The system produces hydrogen fuel for a vehicle constantly during refueling periods with a specified production level, in addition to hydrogen production for electricity. In this case study, we assume that it takes 10 hours (10 pm-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 and trips longer than a regular daily commute (4 kg of hydrogen will allow a 220 mile range). With fast refueling vehicles can be refueled within several minutes (approximately 1 kg of hydrogen per minute [6]). I assume the system constantly produces hydrogen fuel for a vehicle (the hydrogen is sent to the storage unit in a fast refueling system) with a specified production level, in addition to hydrogen production for electricity.

Given engineering inputs, energy data, economic inputs, and the assumptions on hydrogen refueling patterns, the optimal size of a tri-generation system is determined by identifying the optimal size of the FC sub-system. Once the optimal size of the FC sub-system is determined, the size of other system components will be determined. A “brute force” exhaustive search algorithm is used to identify the optimal FC sub-system size.

Details of the brute force algorithm and how it is implemented in this study is explained in section 4.3.2.

5.2.1 Results and discussion

Figure 5.3 is generated by the HTS model and illustrates the system operation by demonstrating the daily (24 hour) energy production of a 2 kW slow refueling tri-generation system: January 1, 2008 is shown as an example. The system is grid-connected, so electricity demands can be met from either the FC sub-system or the grid. Because I use a turn down ratio of 1/5, the operation range of the FC sub-system is 0.4 kW to 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 kW - 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 (this is not the actual hydrogen production curve); the vehicle is assumed to be refueled at a constant rate during 10 pm-7 am each day. The curves for heat generated and heat demand are presented as well. For most hours of the day, the heat supply is above the heat demand except for a couple of morning hours, 6am-7am, and the excess heat is discarded through the pipes connecting the hot water tank and sewage system.

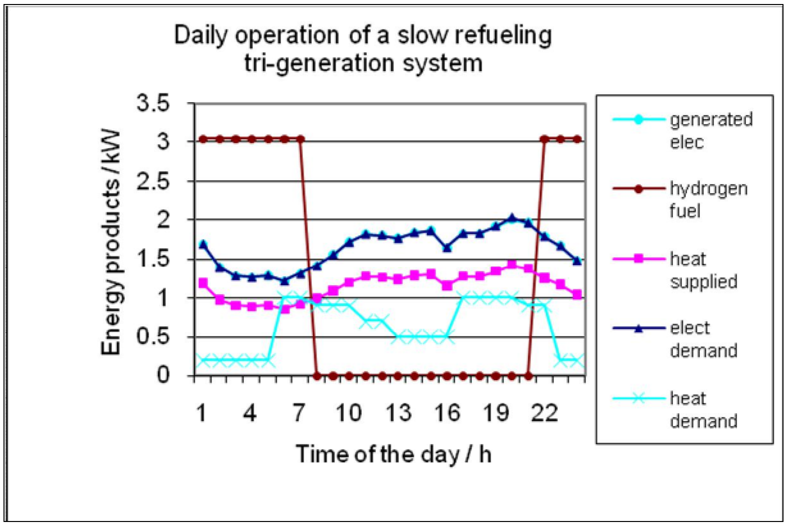

Fig. 5.3 daily operation of a 2 kW electricity load following, slow refueling tri-generation system

Figure 5.4 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 the optimal FC sub-system size can cover. While a larger FC sub-system size could meet a greater fraction of the electricity demand, increased capital cost and lower capital utilization also result. Figure 5.4 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 size of the FC sub-system, 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 5.2, the Sacramento area energy consumption data, and other engineering/economic inputs. FC sub-system sizes smaller than the optimal size lead to higher LEC because the fraction of electricity demand covered by the FC sub-system is lower than what is covered by the optimal size FC sub-system. For FC sub-system sizes larger than the optimal size, higher capital cost, and potential lower utilization lead to higher LEC as well.

As shown in Figure 5.4, 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 FC sub-system size. As expected the optimal size of the FC sub-system is in between the maximum and minimum electricity load.

Figure 5.4 also shows the simulation results for the fast refueling home tri-generation system. 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.

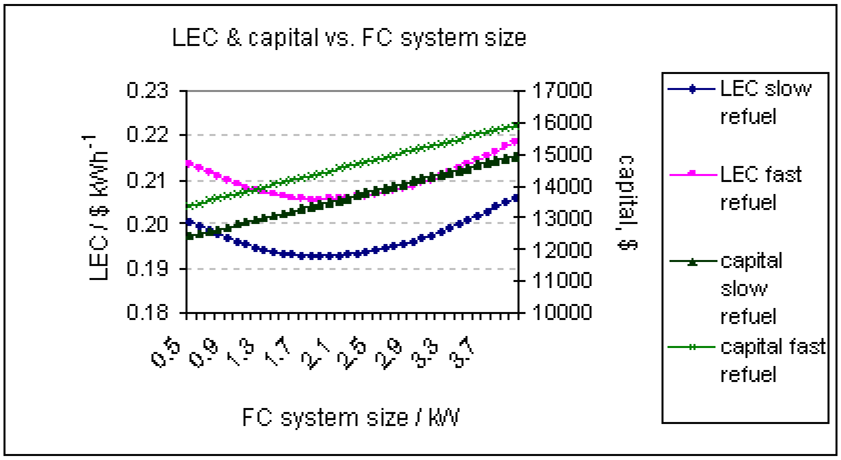

Fig. 5.4 LEC & capital vs. FC sub-system size for slow and fast refueling systems

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%.

5.2.2 Optimal system size sensitivity analysis

Future capital cost and energy prices are subject to uncertainty. Therefore, a sensitivity analysis is conducted for home tri-generation systems to show how the optimal FC sub-system size changes as a result of changes in capital cost and energy prices.

A 20% increase and 20% decrease in gasoline price[11] significantly changes the value of optimal LEC, but have no impact on the optimal FC sub-system size. This suggests that the optimal FC sub-system size is insensitive to gasoline price for a slow refueling home tri-generation system. The reason may be that gasoline price only affects the transportation credit $c_{\text{transport}}$ in equation 4.11, and is independent of the changes in other variables caused by changes of FC sub-system size. Figure 5.5 shows the sensitivity of the optimal FC sub-system size and LEC to gasoline price.

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[11] Based on the projection in "Annual Energy Outlook 2012 Early Release" from the U.S. Energy Information Administration (EIA), during the period of 2010-2020 there is a 1.8% annual growth in gasoline price. This gives a roughly 20% increase in gasoline price in 10 years. The electricity and NG price is less variable, and the changes are with the minus and plus 20% range as well.

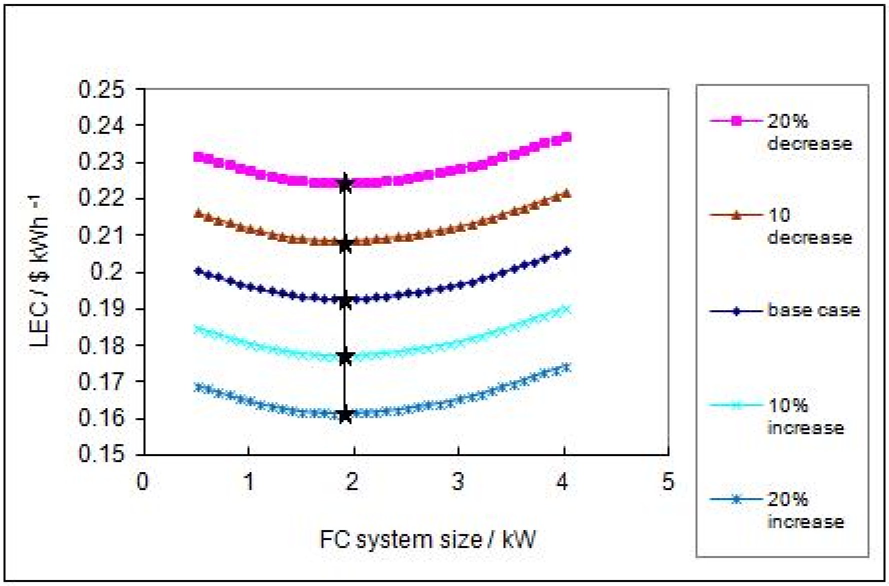

Fig. 5.5 the sensitivity of the optimal FC sub-system size and LEC to gasoline price (slow refueling)

The optimal FC sub-system size is relatively sensitive to capital cost. A 10% increase in capital cost results in a 0.2 kW decrease in the optimal FC sub-system size. The higher the capital cost, the more sensitive the optimal FC sub-system 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[12]. The reason may be that the higher the capital cost, the larger the share of capital cost component in the LEC holding other inputs constant. Figure 5.6 shows the sensitivity of the optimal FC sub-system size and LEC to capital cost.

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[12] Some previous research suggested "The cost reduction achieved, each time cumulative output doubles – known as the learning rate – has been 9–27% for most energy related technologies." [60, 61] I chose minus and plus 20% for our sensitivity analysis, which is within this range.

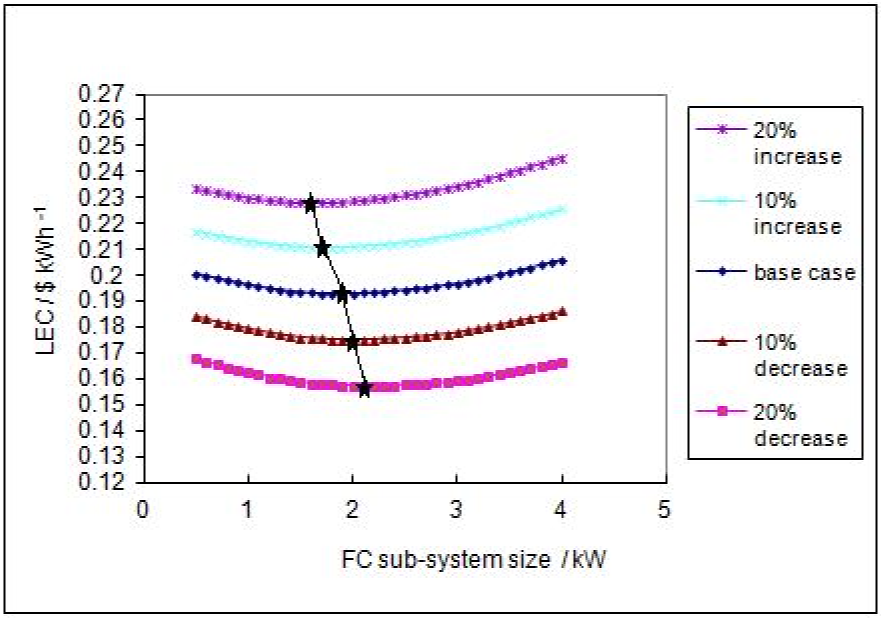

Fig. 5.6 the sensitivity of optimal FC sub-system size and LEC to capital cost (slow refueling)

The optimal FC sub-system size is quite sensitive to the NG and electricity prices. With a 10% and 20% increase in NG price, the shape of the LEC vs. FC sub-system size curves in Figure 5.7 changes and there is no minimum value of LEC on the curve. In this case, the tri-generation system should not be considered because of its poor economic performance. Similar impacts occur for the sensitivity of optimal FC sub-system size and LEC to electricity price as shown in Figure 5.8. A 10% and 20% increase in electricity price results in a 0.1 kW and 0.2 kW increase in the optimal FC sub-system size, respectively. When there is a 10% and 20% decrease in electricity price, the shape of LEC vs. FC sub-system size curves in Figure 5.8 changes, and there is no minimum value of LEC on the curve. As mentioned above, under this condition the tri-generation system should not be considered because of its poor economic performance.

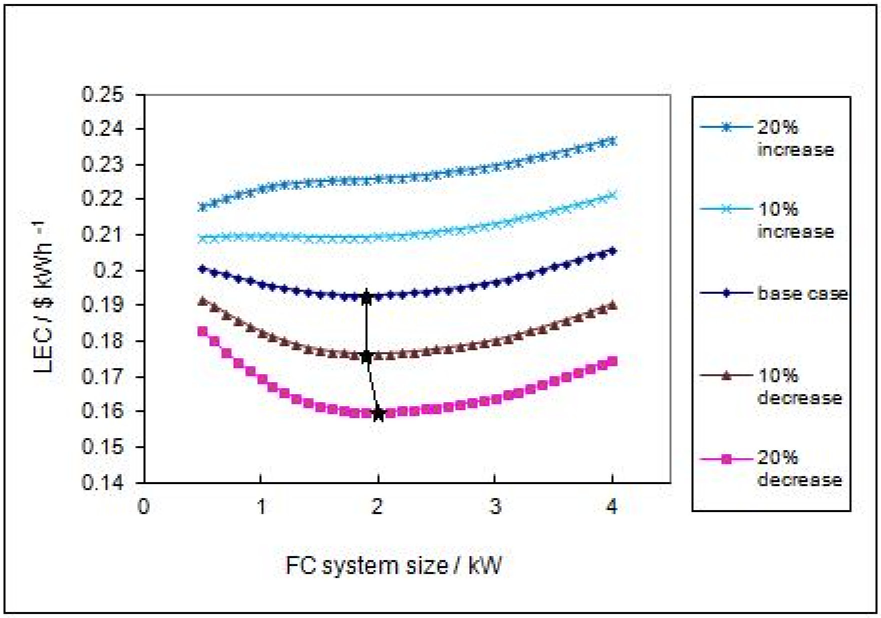

Fig. 5.7 the sensitivity of the optimal FC sub-system size and LEC to NG price (slow refueling)

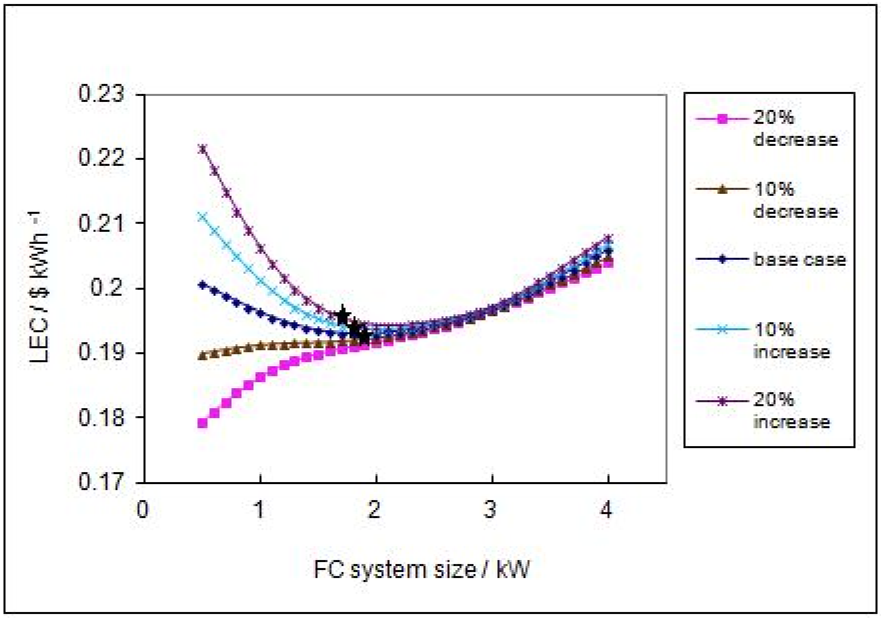

Fig. 5.8 the sensitivity of the optimal FC sub-system size and LEC to electricity price (slow refueling)

A higher NG price or lower electricity price decreases the economic attractiveness of a NG fueled home tri-generation system. This is consistent with the well known fact that the competitiveness of NG fueled co-generation systems is sensitive to the gap between NG and electricity prices. The wider the gap (lower NG price and higher electricity price) the shorter will be the payback period of the NG fueled co-generation systems. Consequently, the NG fueled co-generation systems are more likely to compete economically with the conventional system of grid electricity plus NG heat [62].

The results for fast refueling home tri-generation systems are similar in terms of the trend in the sensitivity, and the simulation results are presented in Figures 5.9 to 5.12.

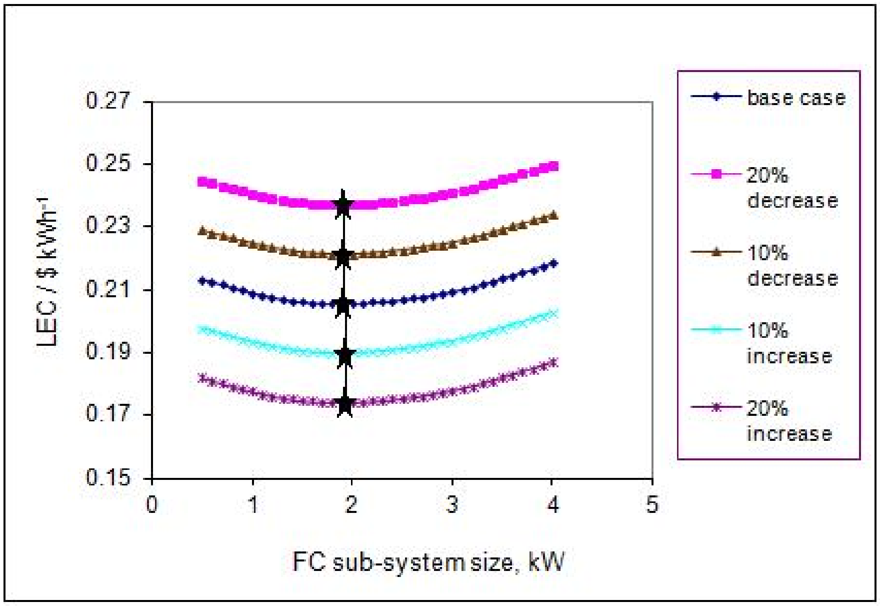

Fig. 5.9 the sensitivity of optimal FC sub-system size and LEC to gasoline price (fast refueling)

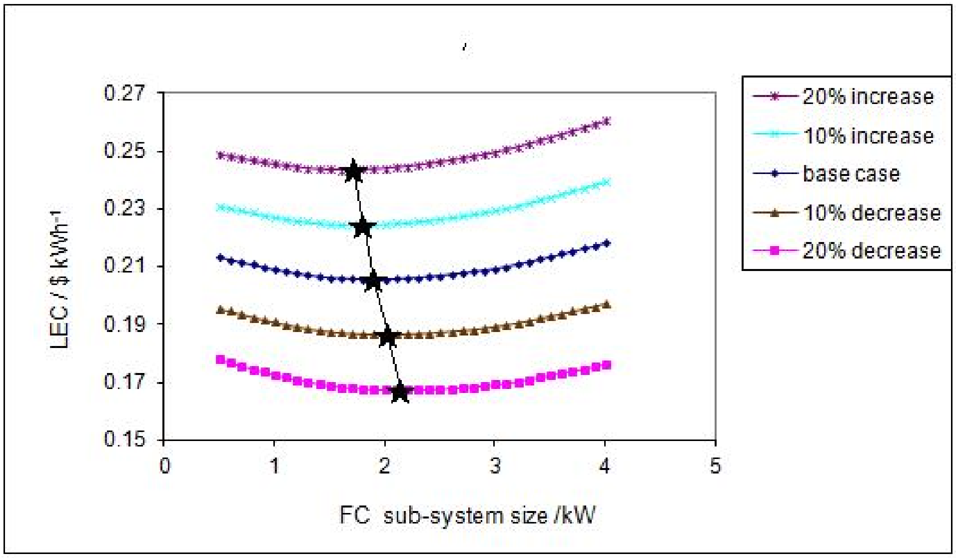

Fig. 5.10 the sensitivity of optimal FC sub-system size and LEC to capital cost (fast refueling)

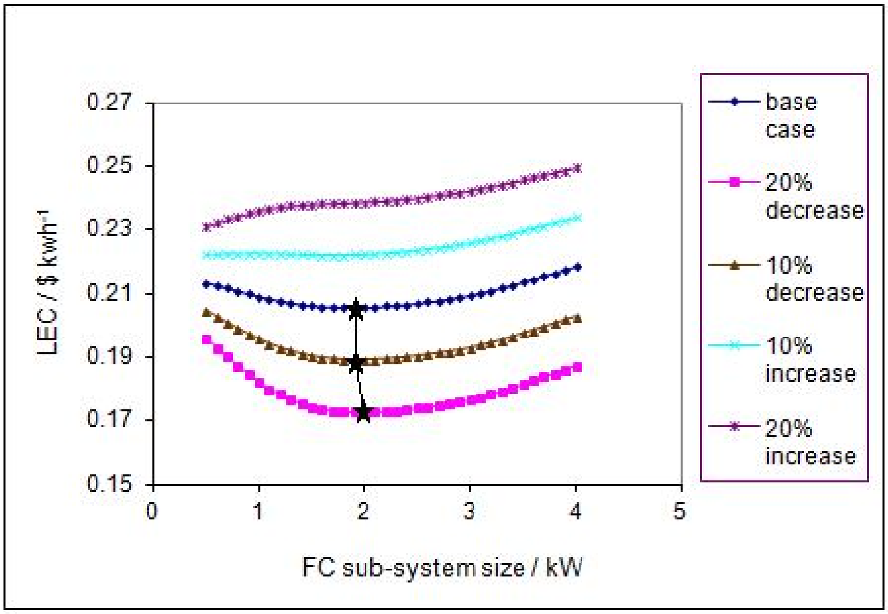

Fig. 5.11 the sensitivity of optimal FC sub-system size and LEC to NG price (fast refueling)

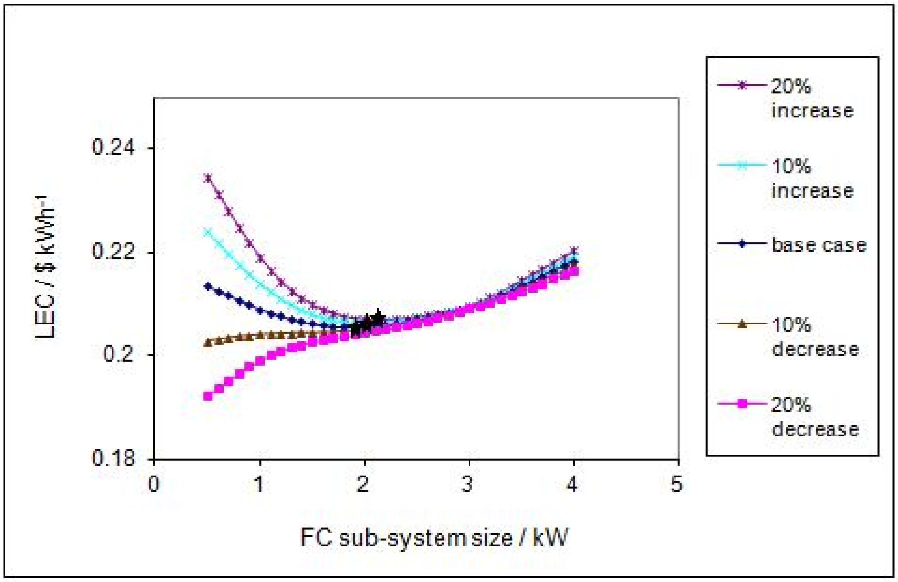

Fig. 5.12 the sensitivity of optimal FC sub-system size and LEC to electricity price (fast refueling)

5.3 The Economics of Operating the 2 kW Tri-Generation System

5.3.1 Results and discussion

This case study evaluates tri-generation systems with a 2 kW capacity for both the slow and fast refueling patterns in detail because manufacturers are more likely to provide system capacity on a 0.5 kW or 1 kW increment and it is closest to the 1.9 kW optimal FC sub-system size identified in Section 5.2. As described in Section 5.2, the system is grid-connected and operating with an electricity load following strategy. Details on system specifications and system capital cost for both the overnight, slow refueling and the fast refueling systems are presented in Tables 5.4 and 5.5, respectively. As shown in Table 5.5, 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.

Tables 5.4

System specifications for a 2 kW tri-generation system

	Slow refuel	Fast refuel
Maximum electricity output (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 d^{-1})	0.91	0.91
Hydrogen storage capacity (kg)	0	4

Tables 5.5

System capital cost for a 2 kW tri-generation system

	Capital Cost, $	
Component	Slow refuel	Fast refuel
NG reformer	5,354	5,189
PEM system cost (FC stack, 15%; ancillary components, 66%; inverter/controller, 19%)	4,626	4,626
Compressor	1,877	1,620
Storage System	0	1,871
Dispenser	646	688

Hot water cogeneration	0	0
Stack (refurbish every 5 yr, present value)	473	473
Non-equipment (delivery and installation)	770	825
Total installed capital cost	13,745	15,290

The LEC, annual energy cost, and CO_2 emissions of a household adopting the 2 kW slow and fast refueling home tri-generation systems are calculated. These results are compared with the results of two reference systems: the business as usual (BAU) reference system of purchasing grid electricity, NG hot water heat, and gasoline for a conventional gasoline vehicle (with a fuel economy of 25 mpg), and the projected reference system of purchasing grid electricity, NG hot water heat, and hydrogen from an early public refueling station. Table 5.6 presents costs and credits associated with installing and operating the 2 kW slow and fast refueling home tri-generation systems. Table 5.7 shows the LEC and its components for both systems.

Table 5.6

Costs and credits of installing and operating the 2 kW tri-generation systems

	Slow refuel	Fast refuel
System capital cost, $	13,745	15,290
CRF	0.149	0.149
System Capital Cost (annualized), \$ y^{-1}	2,127	2,278
NG input, \$ y^{-1}	2,243	2,243
Grid electricity, \$ y^{-1}	74	74
Heat credit, \$ y^{-1}	-278	-278

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}	11,890	11,890

Table 5.7

The LEC and its components for the 2 kW tri-generation systems

	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
PG & E average electricity price, ¢ kWh^{-1}	16.8	16.8
Annual electricity cost with tri-generation system, $\$$ y^{-1}	2,294	2,445
Annual cost for grid electricity, $\$$ y^{-1}	1,997	1,997

As can be seen in Tables 5.6 and 5.7, capital cost, NG cost, and gasoline credit are major components of LEC. The economics of installing and operating a home tri-generation system are expected to be sensitive to these three cost components; quantitative sensitivity analysis will be given in Section 5.3.2.

For a slow refueling home tri-generation system, the LEC is about 19.3 ¢ kWh^{-1} with a capital cost of $13,745. The LEC is 2.5 ¢ kWh^{-1} higher than the 16.8 ¢ kWh^{-1} electricity price. The annual electricity cost from a tri-generation system is $ 2,294, while buying electricity from the grid is $1,997. There is a 14.9% or $297 increase in the annual electricity cost, using the tri-generation system, as compared to purchasing grid electricity. These results indicate using the slow refueling home tri-generation system is more expensive than the BAU reference system (grid electricity, NG hot water heat, and gasoline).

For a fast refueling home tri-generation 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} electricity price. The annual electricity cost from a tri-generation system is $2,445. There is a 22.4 % or $448 increase in the annual electricity cost using tri-generation system, compared with purchasing electricity from the grid. Compared with the slow refueling system, there is a 7.6% or $151 increase in the annual electricity cost. The fast refueling home tri-generation system is more expensive than the BAU reference system as well.

There is a 20.52% or 2,892 kg reduction in annual CO_2 emission using a tri-generation system for both slow and fast refueling patterns relative to the BAU reference system. Figure 5.13 presents a comparison of CO_2 emissions in the three cases: the BAU reference system, the slow refueling home tri-generation system, and the fast refueling home tri-generation system.

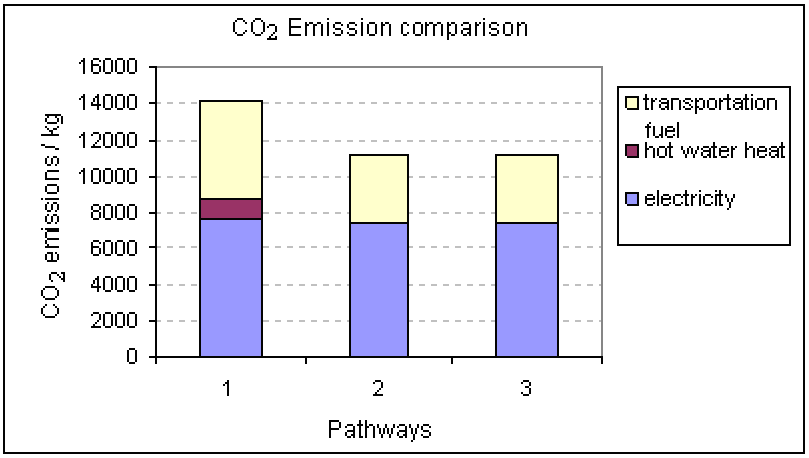

Fig. 5.13 CO_2 emission chart

Note: 1-the BAU reference system; 2-slow refueling system; 3-fast refueling system

Thus far, I have focused on estimating the LEC based on Equation 4.12. If we instead, fix the electricity price, we can develop an analogous equation for calculating the levelized hydrogen cost (see Equation 4.13). 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 an FCV has a fuel economy of 55 mpgge 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.

In other words, holding other inputs constant, if the gasoline price exceeds \$3.61 gallon^{-1} (in 2008 dollars), the tri-generation system can be economically competitive with the BAU reference system. This price is \$0.49 higher than the \$3.12 gallon^{-1} average gasoline price in 2008, which represents a 15.7% increase to the \$3.12 gallon^{-1} price. The levelized hydrogen cost for a fast refueling home tri-generation system is \$8.51 kg $^{-1}$, giving an equivalent gasoline price of \$3.86 gallon^{-1}.

The hydrogen costs of \$7.95 kg $^{-1}$ and \$8.51 kg $^{-1}$ are both 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 per day);
- \$37 kg $^{-1}$ in 2012-2014, 3,442 FCVs and 16-30 stations (using an average of 2,410 kg H_2 per day);
- \$13 kg $^{-1}$ in 2015-2017, 25,000 FCVs and 36-42 stations (using an average of 17,500 kg H_2 per day).

5.3.2 Sensitivity analysis

From Tables 5.6 and 5.7, we see that the major cost components determining the LEC are the system capital cost, NG price, and gasoline price. The HTS model allows us to evaluate the economic impact of changes in capital cost and energy prices. It also allows us to explore the impact of various credits on the economic performance of tri-generation systems. These credits could be policy driven for example, a feebate, tax incentive, or a credit that could reflect a consumer’s WTP for the convenience and security of home refueling. I estimate the LEC for a case with a \$3,000 WTP credit, based on experience with home refueling for CNG vehicles (In a revealed preference estimation it was found that CNG vehicle users pay around \$3,000 for their home refueling systems for CNG vehicles [13]) .

Sensitivity analysis for how the LEC and economic performance of home tri-generation systems 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 of the BAU reference system. A $3,000 WTP credit is equivalent to a 21% decrease in capital cost. The impact of carbon tax is evaluated by imposing a carbon tax of $25, $50, and $75 per metric tonne CO_2 emissions[13] to the base case of the BAU reference system, respectively. Sensitivity analysis results are summarized in Figure 5.14 and Table 5.8. In each case, it is informative and interesting to compare the cost of electricity from the tri-generation system with the price of grid electricity.

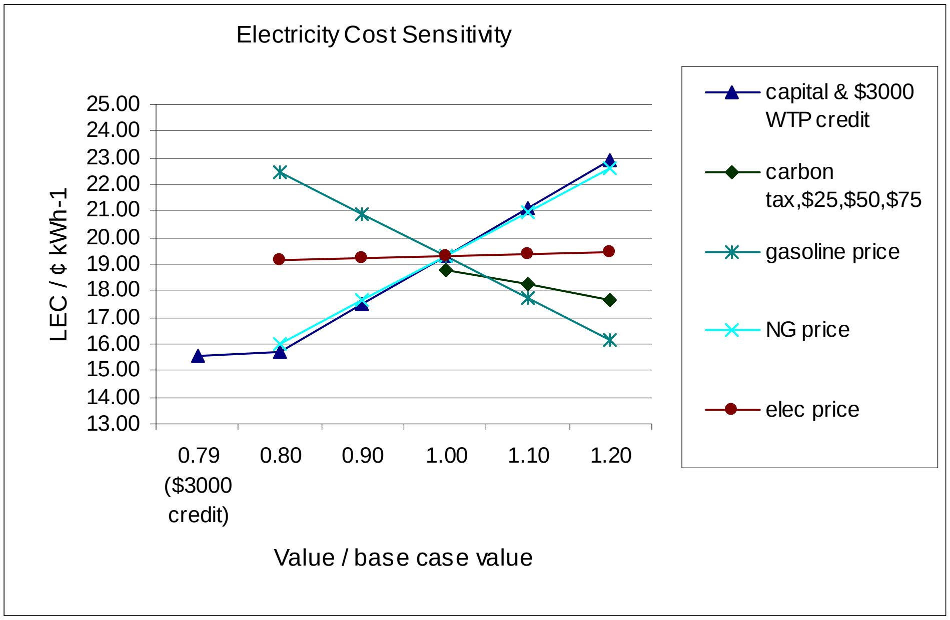

Fig. 5.14 The sensitivity of LEC to capital cost, energy prices and carbon tax (for slow refueling home tri-generation system)

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[13] According to the IPCC literature review of references [63] , most estimates of carbon tax are within the $50 to $100 per metric tonne CO_2 emission range. I chose the amount of $50 per ton, which is at the low end of the range.

Table 5.8

The Sensitivity of LEC to capital cost, energy prices and carbon tax (for slow refueling home tri-generation system)

	$3000 WTP credit (equivalent to 21% decrease in capital)	20% decrease	10% decrease	base case	10% increase	20% increase
value/base case value	0.79	0.80	0.90	1.00	1.10	1.20
LEC with changes in capital cost, ¢ kWh^{-1}	15.54	15.72	17.51	19.30	21.09	22.88
LEC percent change	-19.5%	-18.5%	-9.3%	0.0%	9.3%	18.5%
elec price, ¢ kWh^{-1}	16.80	16.80	16.80	16.80	16.80	16.80
LEC-elec price, ¢ kWh^{-1}	-1.26	-1.08	0.71	2.50	4.29	6.08
LEC with changes in gasoline price, ¢ kWh^{-1}		22.45	20.87	19.30	17.72	16.15
LEC percent change		16.3%	8.2%	0.0%	-8.2%	-16.3%
elec price, ¢ kWh^{-1}		16.80	16.80	16.80	16.80	16.80
LEC-elec price, ¢ kWh^{-1}		5.65	4.07	2.50	0.92	-0.65

LEC with changes in NG price, ¢ kWh^{-1}	15.99	17.64	19.30	20.95	22.60	
LEC percent change	-17.1%	-8.6%	0.0%	8.6%	17.1%	
elec price, ¢ kWh^{-1}	16.80	16.80	16.80	16.80	16.80	
LEC-elec price, ¢ kWh^{-1}	-0.81	0.84	2.50	4.15	5.80	
LEC with changes in Elec price, ¢ kWh^{-1}	19.17	19.23	19.30	19.36	19.42	
LEC percent change	-0.6%	-0.3%	0.0%	0.3%	0.6%	
elec price, ¢ kWh^{-1}	13.44	15.12	16.80	18.48	20.16	
LEC-elec price, ¢ kWh^{-1}	5.73	4.11	2.50	0.88	-0.74	
LEC with Carbon tax (0, \$25, \$50, \$75),¢ kWh^{-1}			19.30	18.76	18.22	17.68
LEC percent change			0.0%	-2.8%	-5.6%	-8.4%
elec price, ¢ kWh^{-1}			16.80	16.80	16.80	16.80
LEC-elec price, ¢ kWh^{-1}			2.50	1.96	1.42	0.88

As shown in Figure 5.14 and Table 5.8, the LEC and the economic performance of a slow refueling home tri-generation system is most sensitive to system capital cost, followed by NG price, electricity price, and gasoline price. A 10% reduction in total system capital cost results in a 9.3 % (-1.7 ¢ kWh^{-1}) decrease in LEC. A 10% increase in NG price leads to an 8.6% increase in LEC. A 10% decrease in gasoline price results in an 8.2% increase in LEC. A higher gasoline price allows more credit, and thus improves the economics of home tri-generation systems.

Although changes in electricity price do not lead to significant changes in LEC, the economic performance of slow refueling home 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 BAU reference system.

A 14% reduction in system capital cost would give a LEC that is competitive with the grid electricity of 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 14% reduction in total system capital cost is equivalent to a 42% decrease in the FC sub-system cost, from $2,300 per kW to $1,350 per kW. For FC sub-system costs less than about $1,350 per kW, the slow refueling home tri-generation system becomes competitive, holding all the other base case assumptions constant.

A $3,000 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 the BAU reference system.

A carbon tax of $25, $50, and $75 per metric tonne of CO_2 emissions results in a 2.8%, 5.6% and 8.4% decrease in LEC, respectively. The results suggest that carbon tax has positive impact on the economic performance of home tri-generation systems, but carbon policy alone is not enough to make home tri-generation competitive with the BAU reference system, unless carbon emissions are priced at significantly higher values.

The slow refueling home tri-generation system is not economically competitive with the BAU reference system 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 \$3,000 credit, or a 20% increase in gasoline price could enable the home tri-generation to compete with the BAU reference system. A 20% decrease in NG price and a 20% increase in electricity price also enables the home tri-generation system to compete with the BAU reference system.

The impact of changing the capital cost and energy prices for a fast refueling system is similar in terms of the trend of sensitivity, and the simulation results are summarized in Table 5.9.

Table 5.9

The Sensitivity of LEC to capital cost, energy prices and carbon tax (for fast refueling home tri-generation system)

	20% decrease	10% decrease	base case	10% increase	20% increase
value/base case value	0.80	0.90	1.00	1.10	1.20
LEC with changes in capital cost, ¢ kWh^{-1}	16.73	18.65	20.57	22.48	24.40
LEC perc change	-18.6%	-9.3%	0.0%	9.3%	18.6%
elec price, ¢ kWh^{-1}	16.80	16.80	16.80	16.80	16.80
LEC-elec price, ¢ kWh^{-1}	-0.07	1.85	3.77	5.68	7.60

LEC with changes in gasoline price, ¢ kWh^{-1}	23.72	22.14	20.57	18.99	17.42	
LEC perc change	15.3%	7.7%	0.0%	-7.7%	-15.3%	
elec price, ¢ kWh^{-1}	16.80	16.80	16.80	16.80	16.80	
LEC-elec price, ¢ kWh^{-1}	6.92	5.34	3.77	2.19	0.62	
LEC with changes in NG price, ¢ kWh^{-1}	17.26	18.91	20.57	22.22	23.87	
LEC perc change	-16.1%	-8.0%	0.0%	8.0%	16.1%	
elec price, ¢ kWh^{-1}	16.80	16.80	16.80	16.80	16.80	
LEC-elec price, ¢ kWh^{-1}	0.46	2.11	3.77	5.42	7.07	
LEC with changes in Elec price, ¢ kWh^{-1}	20.44	20.50	20.57	20.63	20.69	
LEC perc change	-0.6%	-0.3%	0.0%	0.3%	0.6%	
elec price, ¢ kWh^{-1}	13.44	15.12	16.8	18.48	20.16	
LEC-elec price, ¢ kWh^{-1}	7.00	5.38	3.77	2.15	0.53	
LEC with Carbon tax (0, \$25, \$50, \$75),¢ kWh^{-1}			20.57	20.03	19.49	18.95
LEC percent change			0.0%	-2.6%	-5.2%	-7.9%

elec price, ¢ kWh^{-1}	16.80	16.80	16.80	16.80
LEC-elec price, ¢ kWh^{-1}	3.77	3.23	2.69	2.15

5.4 Chapter Summary

In Chapter 5, I apply the interdisciplinary framework and engineering/economic model (HTS model) to evaluate the design, and technical, economic, and environmental performances of home refueling tri-generation systems for co-production of residential electricity, hot water heat, and hydrogen for refueling vehicles. I focus on NG fueled home tri-generation systems, but these methods can also be applied to other energy systems such as tri-generation systems using bio-methane as feedstock, and electrolyzer stations powered by the grid or renewable electricity. Real world electricity consumption data and energy prices (for year 2008) are used in the case studies for a representative single-family residence in northern California Sacramento area.

The optimal FC sub-system size of the home tri-generation systems is found to be 1.9 kW for both slow and fast refueling cases. For the base case assumptions (with an FC sub-system cost of $2,313 per kW), the LEC is estimated to be 19.3 ¢ kWh^{-1} and 20.6 ¢ kWh^{-1}, for slow and fast refueling home tri-generation systems, respectively. These results can be tied to the difference in the consumer's WTP for slow and fast refueling services, and if we have an accurate estimation of this WTP difference, we can predict which system will be more preferable to consumers. The LEC is relatively insensitive to the FC sub-system size around a broad minimum centered at 1.9 kW: for instance, changing the system size by 1 kW increases the electricity cost by less than 2%. The optimal FC sub-system size is insensitive to gasoline price, relatively sensitive to capital cost, and quite sensitive to NG and electricity price within the boundaries of each sensitivity analysis.

A higher NG price or lower electricity price decreases the economic attractiveness of a NG fueled tri-generation system. The competitiveness of tri-generation systems is sensitive to the gap between NG and electricity prices. The wider the gap (lower NG price and higher electricity price) the shorter will be the payback period of the tri-generation systems.

I evaluate a range of 2 kW systems for home tri-generation, considering two different operating strategies: slow and fast refueling. I compare the cost of providing home electricity, hot water heat, and hydrogen transportation fuel with the tri-generation system to the BAU reference system (using grid electricity, NG hot water heat, and gasoline). Home tri-generation is generally a more expensive option than the BAU reference system. For the base case assumptions, the LEC with tri-generation is about 2.5 ¢ kWh^{-1} to 3.8 ¢ kWh^{-1} higher than the 16.8 ¢ kWh^{-1} grid electricity price.

I also compare the cost of adopting the home tri-generation systems to the projected reference system (using grid electricity, NG hot water heat, and hydrogen from an early hydrogen station). I assume the electricity price equals the grid price, and solve for the levelized hydrogen cost, which is found to be \$7.95 kg^{-1} to \$8.51 kg^{-1}. This is equivalent to a gasoline price of \$3.61 $gallon^{-1}$ to \$3.86 $gallon^{-1}$ on a cents per mile basis, accounting for the higher fuel economy of a FC car compared to a conventional gasoline car. The levelized hydrogen cost of \$7.95 kg^{-1} to \$8.51 $kg^{-1}$is highly competitive with the hydrogen cost from an early public hydrogen refueling station (recent research suggests that hydrogen can cost \$13-\$77 per kg from an early, underutilized station).

The LEC and economic performance of a tri-generation system is sensitive to credits and changes in capital cost and energy prices, which have the potential to make home tri-generation competitive with the BAU reference system.

For example, a 14% reduction in capital cost, a \$3,000 credit, or a 20% increase in gasoline price could enable home tri-generation to compete with the BAU reference system. 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 some CO_2 emission reduction (20.52%) associated with home tri-generation compared to the BAU reference system. Carbon taxes have a modest, positive impact on the economic performance of home tri-generation system (For a carbon tax of \$50 per metric tonne CO_2 emissions, 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 the BAU reference system unless capital costs are reduced, or energy prices change (NG price decreases, and/or electricity and gasoline price increases). In Chapter 6, I will analyze neighborhood refueling using tri-generation systems, and I expect the economy of scale would further improve the economic performance of tri-generation systems.

Chapter 6: Neighborhood Refueling Case Studies for Multi-family Residences

In Chapter 6, I evaluate neighborhood tri-generation systems for multi-family residences such as apartment complexes and town houses. Neighborhood tri-generation systems can also be installed at a community of single family houses, serving multiple households, as long as it is economical to install and operate these systems based on demand profiles and other inputs such as energy prices. More discussion on neighborhood refueling is provided in Section 2.4.

It is worth noting that there are significant number of people who live in multi-family residences, and these people are not necessarily poor and should be included as target populations for a mass produced FCV. The US Census Bureau data released in September, 2010 [64] showed that "the number of multifamily households in the U.S. jumped 11.7 percent from 2008 to 2010, reaching 15.5 million, or 13.2 percent of all households. It is the highest proportion since at least 1968, accounting for 54 million people". In big metropolitan areas such as San Francisco, New York, and Los Angeles the percentages are higher. For example, based on the U.S. Census Bureau statistics, in California the percentage of housing units in multi-unit structures is estimated to be 30.7% during 2006-2010 period. The percentage for San Francisco County is even higher reaching 66.6% [65]. In addition, there are significant demographic trends that indicate a continuing and growing demand for multifamily housing in the US [66]. Additionally, in many areas outside the U.S. such as Europe and Asia, where the land use pattern in cities is more dense, the percentage of multi-family housing is expected to be high as well.

The perception some people have that those who live in multi-family housing out of circumstance (cannot afford a single family house) is not necessarily true, and more and more people live in multi-family housing out of choice. "For the past five years, households making $50,000 per year or more have constituted the fastest-growing segment of the apartment market. Many renters in this income bracket who could afford to purchase single-family housing chose instead to rent. Higher-income households constitute the fastest-growing segment of the apartment market. Many of these households want luxury amenities and choose urban living for the convenient lifestyle it offers." [66] Additionally, in many areas outside the U.S. such as Europe and Asia, it is not uncommon for middle and upper middle class households to live in townhouses and apartments.

I assume that these neighborhood tri-generation systems can be designed as a vending machine-like unit in terms of size and installation. I assume that these systems can be easily installed in or near existing buildings [18]. I consider neighborhood refueling systems sized for 10-20 households. The average hydrogen output capacity is approximately 10-20 kg d^{-1}, which is larger than individual home systems, but smaller than public hydrogen refueling stations that typically offer at least 100 kg d^{-1} of hydrogen[14]. Compared to home tri-generation systems for single family residences, the larger size of neighborhood systems has the potential to improve efficiency and lower costs through economies of scale.

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[14] Actual output capacity is given later in system specifications.

6.1 Energy Demand Data and Key Engineering/economic Inputs

Similarly, as described in Section 5.1, because tri-generation systems are designed to provide electricity, hot water heat, and transportation fuel to residences, three sets of energy consumption data are used in neighborhood refueling case studies for multi-family residences: the hourly electricity demand profile, hourly hot water demand profile, and hourly transportation fuel consumption data.

I employ electricity demand data for a representative multi-family residence in the Northern California Sacramento area, provided by the California Energy Commission [55]. The residence is assumed to be a 10-household apartment building. It is also assumed that passenger vehicles in the households are driven 10,000 miles each year[15], with a fuel economy of 25 mpg for a conventional gasoline vehicle and 55 miles per kg of H_2 for an FCV. In recent years, hybrid electrical vehicles (HEV) have gained some acceptance among consumers. To reflect the recent trend in industry and research, I evaluate the impact of replacing the conventional gasoline vehicle with an HEV as well. The fuel economy of an HEV is assumed to be 40 mpg. The fuel economy assumptions are approximately the same as in some other studies [3, 67].

Figure 6.1 shows the ordered hourly electricity load profile used in this chapter. As can be seen, most of the time (80%), the electricity demand load is below 8 kW.

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[15] Some studies [58] find that on average people in multi-family residences drive less compared with people in single family residences due to issues such as transportation cost burden and land use density. Therefore, we use lower annual miles driven range found in the literature [59]. Specifically, we use 10,000 miles per year in this chapter, instead of the 15,000 miles per year used in the home refueling case studies for single family residences in Chapter 5. See the footnote in page 58.

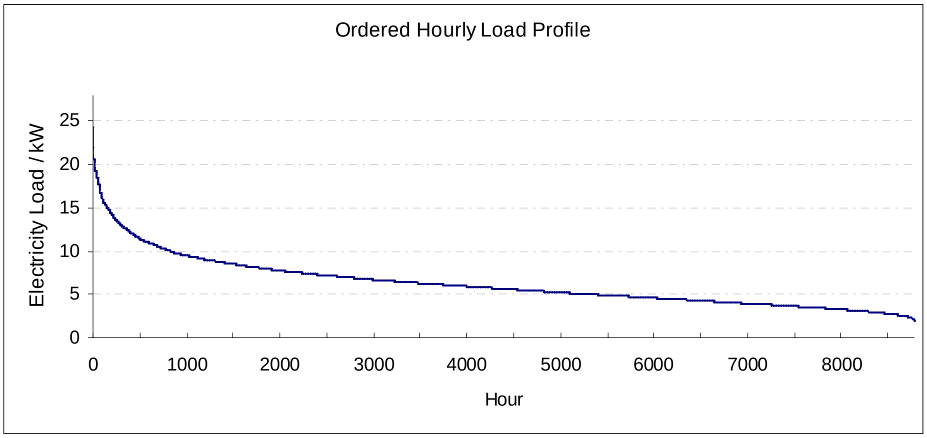

Fig. 6.1 Ordered annual hourly electricity load profile
(The graph shows the number of hours per year the electricity load exceeds a certain value (there are 8,784 hours in the year 2008))

A 24-hour hot water demand profile is used to represent the 366 days of the year 2008, which is derived from [16, 56]. The data from [16, 56] was directly used in the home refueling case studies for single family residences in Chapter 5. In this chapter, the data is multiplied with the ratio of annual total electricity consumption in a multi-family residence household to the annual total electricity consumption of a single-family residence household to reflect the difference in their hot water heat demand. This assumes that for multi-family residences the hot water demand scales the same way as for single family residences. This assumption is more conservative than using the hot water demand profile for single family residences directly for multi-family residences (I do not have hot water demand profile for multi-family residences), since the annual total hot water energy is less and thus less hot water heat can be captured during the electricity generation process. There are other ways to factor the hot water demand profile as well. For example, I can also factor the profile based on the average numbers of household size for single family and multi-family residences.

As described in Section 5.1, although there are weekly and seasonal variations in hot water heat demand, it is not expected that these variations would affect the modeling results significantly for a few reasons [18]. First, hot water heating daily demand pattern does not vary significantly with seasons. Second, for a typical household in the area under study, the annual total electricity consumption is approximately double the annual total hot water energy consumption, and the distribution and two peaks of electricity hourly profile match the distribution and peaks of the hot water heat demand profile well. 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 [17, 18]. Figure 6.2 shows the 24-hour electricity and hot water heat demand profiles of a particular day (January 1, 2008) to show the demand patterns. 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 over time.

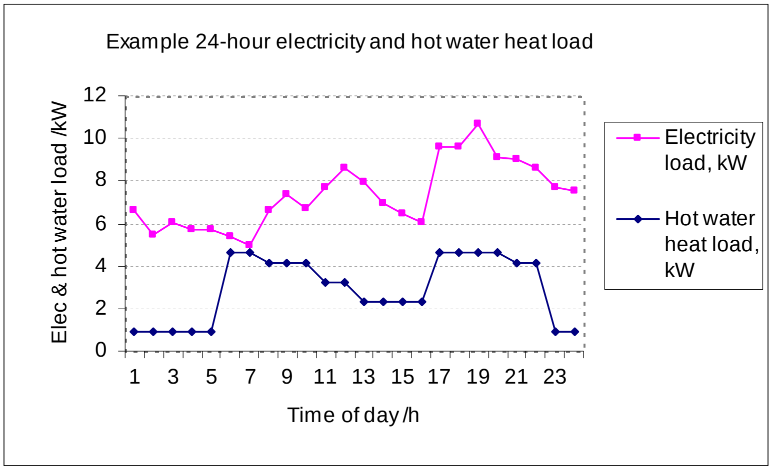

Fig. 6.2 Hourly electricity and hot water demand profiles (source: [16, 56])
Note: Both electricity and hot water profiles are derived by multiplying the single residence profiles by ten (the number of households in the multi-family residence). The

actual aggregated demand for both would probably be less “peaky” (i.e., the maximum demand divided by the average demand would be less), because individual households’ demands would not coincide exactly in time.

Because the refueling pattern of the passenger vehicles of the 10 households is variable, it is not possible to have an hourly transportation demand profile. Estimation and assumptions have to be made on the best available data for transportation demand profile in these case studies. Section 6.2 presents details on the assumptions on refueling patterns and transportation demand profile used in this chapter.

Table 6.1 summarizes the annual energy consumption of the aforementioned electricity demand profile, hot water heat demand profile, and transportation fuel demand for the 10 households in the residence. The total annual energy consumption of electricity, hot water heat, gasoline, and fuel hydrogen is 54,939.3 kWh (electricity), 25,875.6 kWh (93.17 GJ hot water), 134,780 kWh (4,000 gal gasoline, based on LHV), and 60,598.2 kWh (1,818.18kg hydrogen, based on LHV), respectively. When replacing the conventional gasoline vehicle with a HEV, the total annual energy consumption of gasoline is 84,238 kWh (2,500 gal gasoline).

Table 6.1

Summary of the energy demand data of the multi-family residence

(10 households, 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	6.25	54,939.34	24.34	1.94	2.88

Hot water	2.95 (10.62 MJ/h)	25,875.64 (93.17 GJ)	4.62	0.92	1.51
Hydrogen	n/a	60,598.18 (1,818.18kg)	n/a	n/a	n/a
Gasoline (a conventional gasoline vehicle)	n/a	134,780 (4,000 gal)	n/a	n/a	n/a
Gasoline (an HEV vehicle)	n/a	84,238 (2,500 gal)	n/a	n/a	n/a

In addition to energy demand data, model results also vary with key engineering/economic inputs including efficiencies of energy conversion processes, energy prices, and capital, operating and maintenance costs. Table 6.2 shows key engineering inputs used in this chapter. Tables 6.3 and 6.4 present key economic inputs and cost assumptions, respectively.

Table 6.2

Key engineering inputs

Reformer efficiency [17]	75% (this parameter represents the combined efficiency of fuel reformer, water gas shift processor, and purifier in Figure 4.1)
FC stack efficiency η_{FC}, (also shown in Figure 6.3) [17, 46, 50]	$\eta_{FC} = \{1-\exp[-0.5(P/P_{FC,max})^{1.2}]\}*[0.622-0.002(P/P_{FC,max})]$, 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 [17])
Compressor efficiency [51]	80%
Parasitic load efficiency loss, the percentage of generated electricity	15%

used for parasitic load [46]	
AC/DC power conversion efficiency [17]	92%
H_2 Utilization in the FC sub-system [17]	85%
Hot water tank efficiency (NG to hot water heat) [17]	75%
Rate of heat (by product of electricity generation) captured for hot water [17]	70%

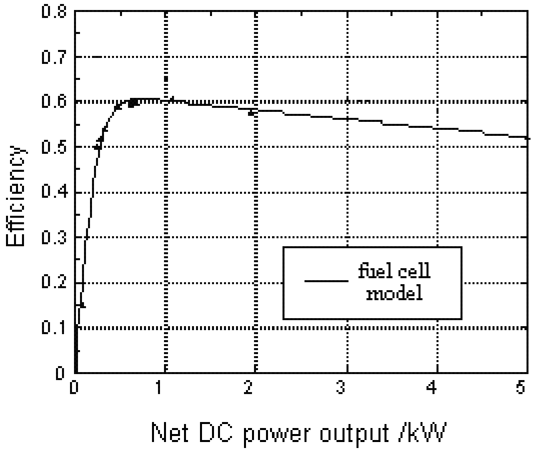

Fig. 6.3 Net DC power to hydrogen efficiency of the FC sub-system (modified from: [17])

Table 6.3

Key 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 [48].
Cost assumptions	The capital cost of a system is the sum of component costs. The FC stack is assumed to be replaced every 5 years. The present value of these replacements is included in the capital cost.

Table 6.4

System component costs (in 2008 dollars)

Component	Cost
NG reformer	6,434.1 + 147.2 $P_{\mathrm{ref,max}}$, ($P_{\mathrm{ref,max}}$ is the capacity of the reformer in kW); This cost formula is developed in [37], the reformer cost calculated based on it is slightly lower than the cost estimate of the DOE H2A Production Analysis for 2005 [68], but higher than the cost projection of the DOE H2A Production Analysis for 2025 [69].
PEM FC sub-system cost	FC stack: $1.1 * \{[(722.45 - 105.4) / 10 + 17.56 * 0.6] * P_{\mathrm{FC,max}} * (1 + 0.06)^5 / 0.625 + 363.33\}$, ($P_{\mathrm{FC,max}}$ is the capacity of the FC stack in kW); Ancillary components: $3{,}161.9 + 37.8 * P_{\mathrm{FC,max}}$; Inverter/controller: $542 + 169 * P_{\mathrm{FC,max}}$; This cost formula is developed in [37], the PEMFC system cost calculated based on it is within the cost range presented in [70], and higher than the estimated cost in [71][16].

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[16] The cost estimation of FC systems we use is consistent with a few references; some of these references such as [71] use a combination of methods: published data, focus groups, surveys, and interviews. Stakeholders including FC system developers, component manufacturers, key industry influencers and DOE, provide inputs to and critical review of the assumptions and conclusions of these references.

Storage System	284 N_t + 192H_{store} (N_t - the number of tanks in the cascade filling storage system, H_{store} - hydrogen stored, kg of hydrogen.); This cost formula is developed in [37], the storage system cost calculated based on it is higher than the DOE cost target for onboard H_2 storage tanks [72], but lower than the cost range of onboard H_2 storage tanks in a 2011 assessment of current technology [72].
Compressor	5,920+374.1 P_{comp}, (P_{comp} is the capacity of the compressor in kg h^{-1}); This cost formula is developed in [37], the compressor cost calculated based on it is higher than the cost estimate of the DOE H2A Production Analysis for current and future technology [68, 69].
Dispenser	856+79*$P_{ref,max}$ This cost formula is developed in [37], the dispenser is assumed to be similar to the ones used in CNG home refueling systems, instead of dispensers used in public stations.
Hot water tank and distribution system	0 (similar tank and distribution system is also necessary for the conventional NG heating system, so there is no incremental cost).
Replacement FC Stack at the 5th year (present value)	Stack cost/$(1+0.08)^5$
Non-equipment (delivery and installation)	23% of total equipment capital cost [73] (I 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).
Maintenance	1,000/y

Note: The cost estimation is based on a 1,000 unit cumulative production volume.

6.2 The Optimal Size of a Neighborhood Tri-Generation System

6.2.1 Results and discussion

As illustrated in Section 4.3.2, optimizing the size of a tri-generation system allows the system to meet three energy needs (electricity, hot water heat, and transportation fuel) with minimal cost under specified energy prices, and other engineering/economic inputs. Given the assumptions on the operation strategy, refueling pattern (and thus fuel hydrogen production rate in addition to hydrogen for the FC sub-system to generate electricity), the optimal size of a tri-generation system is determined by identifying the optimal size of the FC sub-system.

In this chapter, I assume the tri-generation system is grid-connected and operates in an electricity load following mode. The system constantly produces fuel hydrogen for vehicles with a specified production level, in addition to the hydrogen production for the FC sub-system to generate electricity and heat. A hydrogen storage unit is configured in the system to allow flexible, fast refueling. Vehicles can be refueled to a full tank within several minutes (approximately 1 kg of hydrogen per minute [6]). A “brute force” exhaustive search algorithm is used to identify the optimal size. Details of the brute force algorithm and how it is implemented in this study is explained in section 4.3.2.

Figure 6.4, generated based on the simulation results, illustrates the operation of a tri-generation system by demonstrating the daily (24 hour) energy production of a 6.5 kW system for a particular day (January 1, 2008) using the data and inputs described in Section 6.1. The system is grid-connected and operates in an electricity load following mode. However, electricity demand can be met from either the FC sub-system or the grid, depending on the electricity demand at that particular time and the operation range of the FC sub-system. Using a turn down ratio of 1/5, the operation range of the FC sub-system is 1.3 kW – 6.5 kW. If the electricity demand is below 1.3 kW, the FC sub-system will be shut down because its efficiency is low (the reformer is still operating producing hydrogen fuel, which goes to the hydrogen storage tank). If the electricity demand is higher than 6.5 kW, the FC sub-system will be operating at 6.5 kW. The electricity demand above 6.5 kW will be purchased from the grid.

For this particular day, the electricity demand is within the 1.3 kW – 6.5 kW range for eight hours (2-7 am and 3-4 pm), but greater than 6.5 kW for the rest of the day. For hours when electricity demand is within the operating range of the system, the generated electricity and electricity demand curves are the same (load following). For hours when electricity demand is greater than the system capacity (6.5 kW), the FC sub-system is operating at 6.5 kW; the electricity demand above 6.5 kW is purchased from the grid. It is assumed that the reformer is constantly operating to produce hydrogen fuel in addition to hydrogen for electricity. Fuel hydrogen production, i.e., for use in vehicles, is conceptually shown in Figure 6.4 as constant. The total production rate of hydrogen for transportation fuel plus electricity has a shape similar to the generated electricity curve plus the demand for hydrogen fuel. The curves for hot water heat generated and hot water heat demand are presented as well.

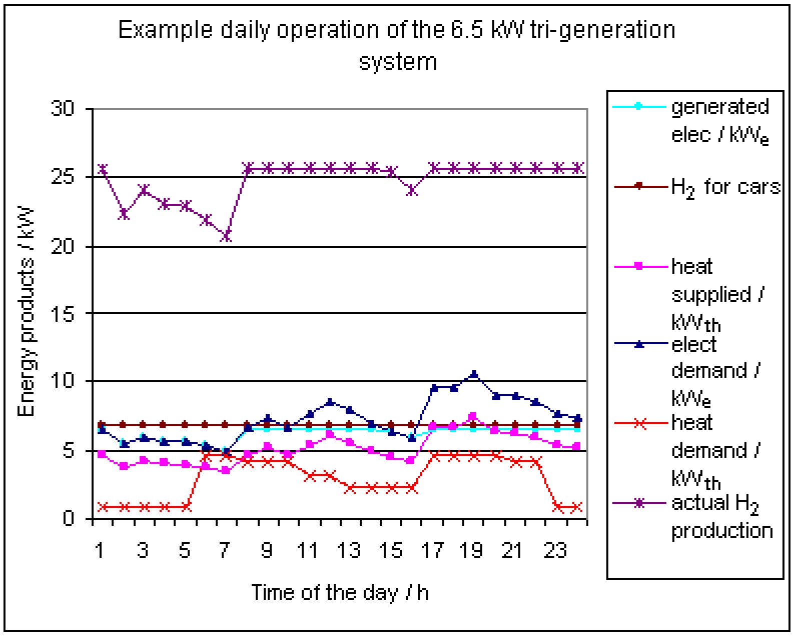

Fig. 6.4 Daily operation of a 6.5 kW tri-generation system
(The FC system follows the electricity demand within its operation range)

Figure 6.5 shows that when determining the optimal FC sub-system size to meet specified power demand, there is a tradeoff between the capacity factor (capital utilization) and the fraction of electricity demand that can be covered by the tri-generation system. While a larger system size could meet a greater fraction of the electricity demand, increased capital cost and lower capital utilization also result. Figure 6.5 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 capacity, because the cost of main components is linear with component capacities. 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 6.3 and the energy consumption data.

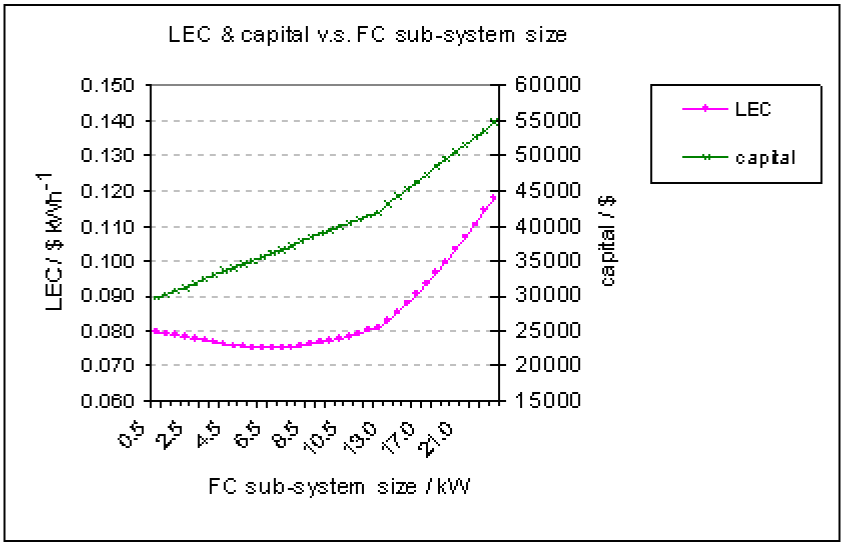

Fig. 6.5 LEC vs. FC sub-system size for tri-generation systems of different sizes

As shown in Figure 6.5, the optimal or lowest LEC point (7.52 ¢ kWh^{-1}) occurs when the capacity of the FC sub-system is around 6.5 kW. This is slightly above the 6.25 kW annual average electricity load. Table 6.5 illustrates the specifications of the 6.5 kW system.

Table 6.5

Specifications of the 6.5 kW tri-generation system

	System specifications
Reformer capacity, kg of H_2 per day (kg d^{-1})	19.35
PEMFC stack capacity, kW	6.5
Number of vehicles supported	10
Fuel H_2 production capacity additional to electricity H_2 capacity, kg d^{-1} (the capacity factor used is 0.63 [37])	7.89 (this supports the average daily demand of 10 vehicles)

Hydrogen storage, kg of H_2 (determined using the formula: $N_{FCV} \times H_{FCV} \times S_f / U_c$, N_{FCV} is the number of fuel cell vehicles supported by the system, H_{FCV} is the average daily hydrogen consumption by one FCV, S_f is the total cascade storage fraction of average daily demand, and U_c is the hydrogen utilization fraction [37].)	12.62 (this capacity approximately allows 3 vehicles to be fast refueled one by one at any time)

Table 6.6

System capital cost for the 6.5 kW tri-generation system (based on Table 6.4)

Component	Capital Cost, $
NG reformer	9,282.4 (or \$480 kg $^{-1}$, this is slightly higher than the \$424 kg $^{-1}$ cost estimate of the DOE H2A Production Analysis for 2005 [68].
PEM system cost (FC stack, 23.5%; ancillary components, 51.6%; inverter/controller, 24.9%)	6,598 (FC stack: 1,551.8, ancillary components: 3,405.7, inverter/controller: 1,640.5) (the FC stack cost is \$239 kW $^{-1}$, and the FC system cost is \$1,015 kW $^{-1}$, the FC system cost is within the \$465-1,395 kW $^{-1}$ cost range presented in [70], and higher than the estimated cost of \$656 kW $^{-1}$ found in [71].)
Compressor	6,221.6 (or \$7,717 kg h $^{-1}$, this is significantly higher than the \$4,537 kg h $^{-1}$ cost estimate of the DOE H2A Production Analysis [68, 69])
Storage System	4,127.5 (or \$327 kg $^{-1}$, this is about 2.5 times the DOE cost target for onboard H_2 storage tanks [72], but lower than the estimation of \$353-656 kg $^{-1}$ cost range of onboard H_2 storage tanks in a 2011 assessment of current technology [72].
Dispenser	\$1,369.5 per dispenser
Hot water cogeneration	0
Stack (replaced at the fifth year, present value)	1,056.2
Non-equipment (delivery and installation)	6,505.6

Total installed capital cost	35,160.8 (\$5,409 kW^{-1})

The LEC shows low sensitivity to the FC sub-system size around a broad minimum centered at 6.5 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 1%.

6.2.2 Optimal system size sensitivity analysis

Future capital cost and energy prices are subject to uncertainty. Therefore, a sensitivity analysis is conducted to show how the optimal FC sub-system size changes as a result of changes in capital cost and energy prices.

The optimal FC sub-system size is insensitive to gasoline 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. Figure 6.6 shows the sensitivity of FC sub-system size and LEC to gasoline price.

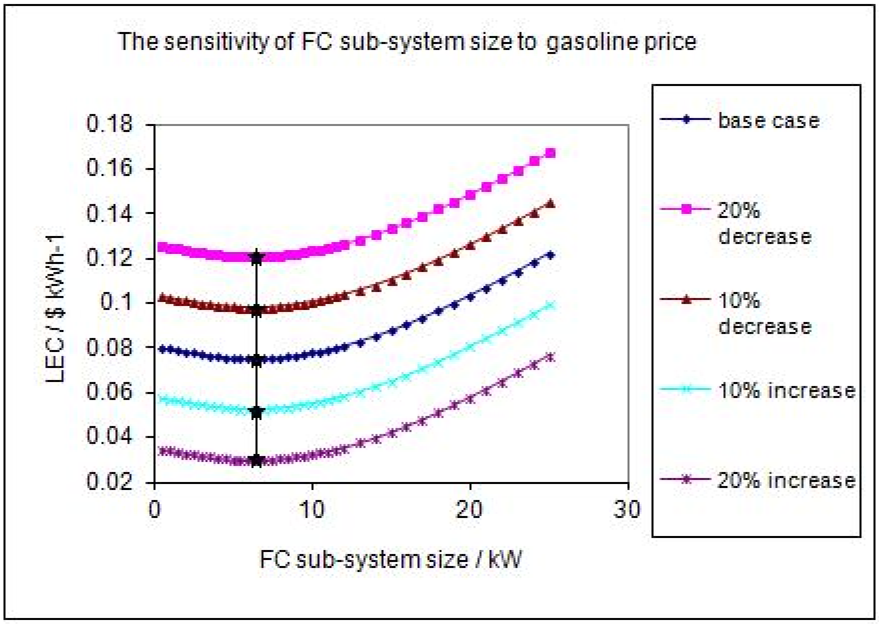

Fig. 6.6 The sensitivity of FC sub-system size to gasoline price (The base case gasoline price is \$3.12 gallon^{-1})

The optimal FC sub-system size is relatively sensitive to capital cost. A 10% and 20% increase in capital cost results in a 1 kW and 1.5 kW decrease in the optimal FC sub-system size, respectively. A 10% and 20% decrease in capital cost results in a 0.5 kW and 1 kW increase in the optimal FC sub-system size, respectively. The results indicate that the higher the capital cost, the more sensitive the optimal FC sub-system size is to capital cost. The reason may be that the higher the capital cost, the larger the share of capital cost component in the LEC holding other inputs constant. Figure 6.7 shows the sensitivity of FC sub-system size to capital cost.

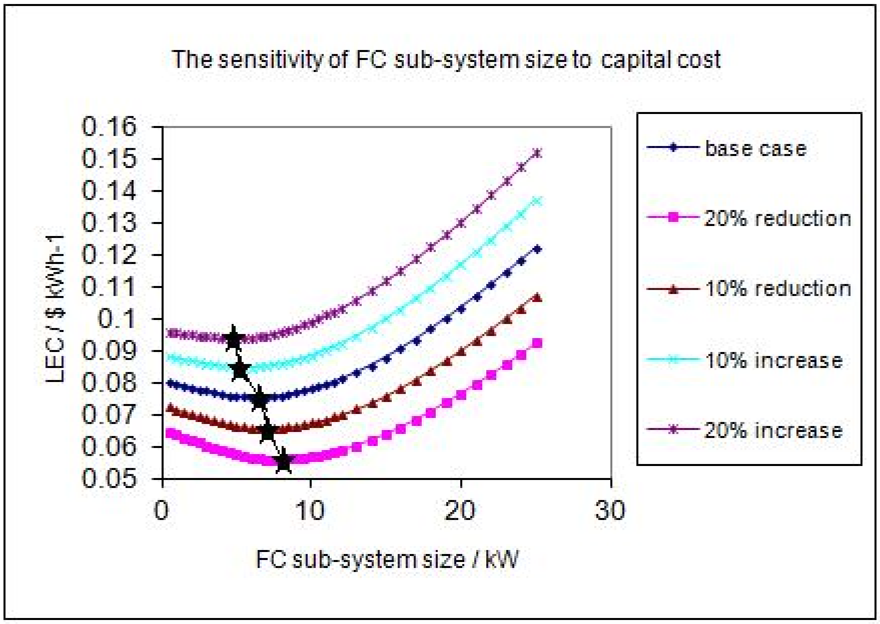

Fig. 6.7 the sensitivity of FC sub-system size to capital cost

The optimal FC sub-system size is quite sensitive to NG and electricity prices. A 10% and 20% decrease in NG price results in a 1 kW and 1.5 kW increase in the optimal FC sub-system size, respectively. When there is a 10% and 20% increase in NG price, the shape of the LEC vs. FC sub-system size curves in Figure 6.8 changes, and there is no minimum FC sub-system size on the curve. In this case, the tri-generation system would not be economically competitive with the conventional option of purchasing grid electricity, NG hot water heat, and gasoline. Similar changes occur for the sensitivity of FC sub-system size to electricity price as shown in Figure 6.9. A 10% and 20% increase in electricity price results in a 1.5 kW and 2 kW increase in the optimal system size, respectively. When there is a 10% and 20% decrease in electricity price, the shape of LEC vs. FC system size curves in Figure 6.9 changes, and there is no minimum FC sub-system size on the curve. A higher NG price or lower electricity price decreases the economic attractiveness of a NG fueled tri-generation system. This is consistent with the well known fact that the economic competitiveness of NG fueled co-generation systems is sensitive to the gap between NG and electricity prices. The wider the gap (lower NG price and higher electricity price) the shorter will be the payback period of the NG fueled co-generation systems. Consequently, the NG fueled co-generation systems are more likely to compete economically with the conventional system of grid electricity plus NG heat [62].

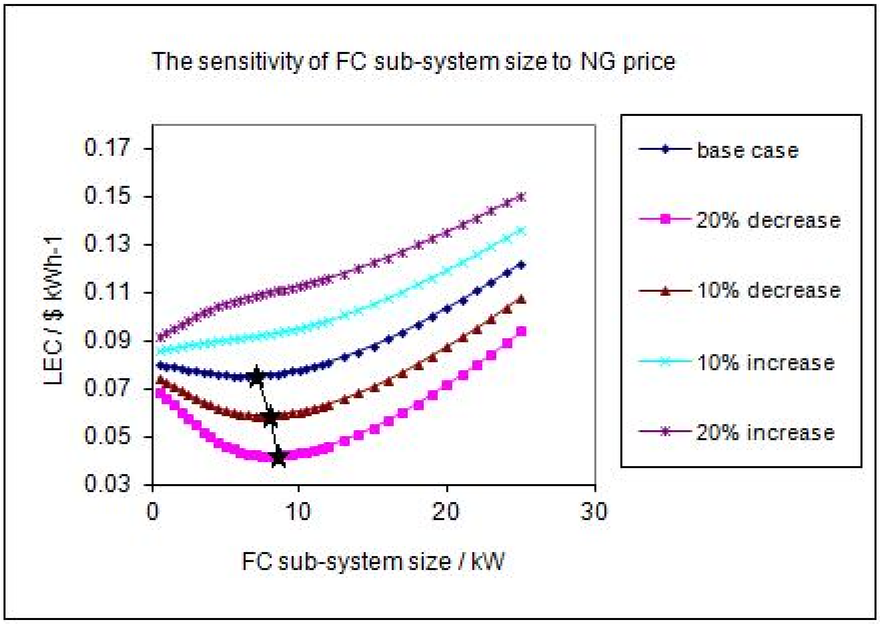

Fig. 6.8 the sensitivity of FC sub-system size to NG price
(Base case NG price is 3.72 ¢ kWh^{-1} or \$10.33 GJ^{-1})

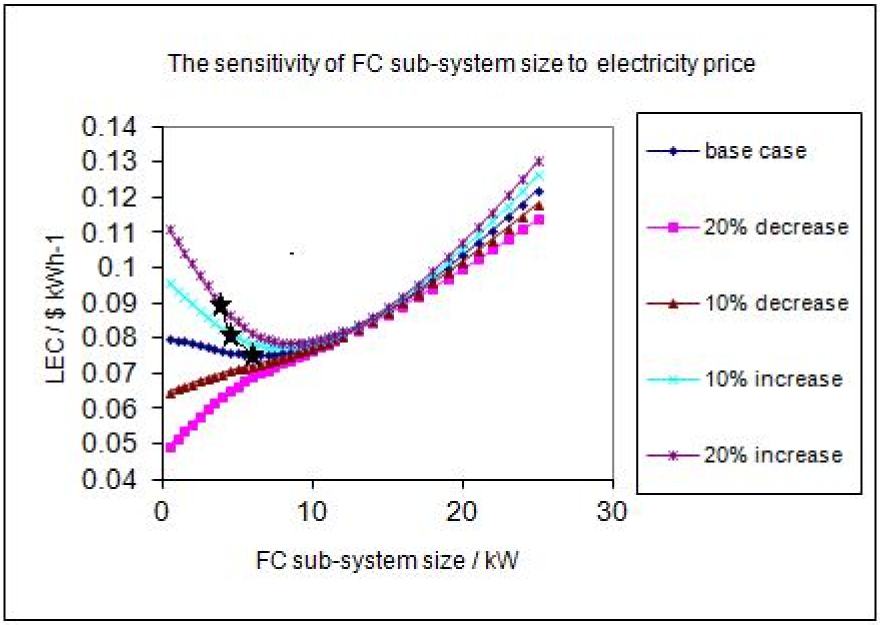

Fig. 6.9 the sensitivity of FC sub-system size to electricity price
(Base case electricity price is 16.8 ¢ kWh^{-1})

6.3 The Economics of Operating the 6.5 kW Tri-Generation System

6.3.1 Results and discussion

This case study investigates the 6.5 kW tri-generation system in detail because it is the optimal size identified in Section 6.2.1. As described in Section 6.2.1, the system is grid-connected with an electricity load following strategy. The HTS model is used to generate the LEC, annual energy cost, and annual CO_2 emissions for the tri-generation system. These results are compared with the results of two reference systems: first, the business as usual (BAU) reference system of purchasing grid electricity, NG hot water heat, and gasoline for the conventional gasoline vehicle described in Section 6.1; and second, the projected reference system of purchasing grid electricity, NG hot water heat, and hydrogen from an early public station for the FCV described in Section 6.1.

Details on the specifications and capital cost of the 6.5 kW tri-generation system are presented in Tables 6.5 and 6.6, respectively. As shown in Table 6.6, a NG reformer is the biggest contributor to total capital cost, followed by the PEM FC sub-system (including PEM FC stack, ancillary components and inverter/controller), compressor, and storage system. Table 6.7 presents all costs and credits associated with installing and operating the 6.5 kW tri-generation system during the lifetime of the system, as well as the LEC and its components.

Table 6.7

Costs and credits of installing and operating the 6.5 kW neighborhood tri-generation system

Costs and credits		The LEC and its components	
System capital cost (including the FC stack replacement cost at the fifth year), $	35,161	Total electricity provided by the system, kWh	54,939
System Capital Cost (annualized), $ y^{-1}	5,239	System capital cost (annualized), ¢ kWh^{-1}	9.54
Fixed O&M Costs, $ y^{-1}	1,000	Fixed Operating Costs, ¢ kWh^{-1}	1.82
NG input, $ y^{-1}	10,215	NG input, ¢ kWh^{-1}	18.59
Grid electricity, $ y^{-1}	1,441	Grid electricity, ¢ kWh^{-1}	2.62
Heat credit, $ y^{-1} (NG)	-1,283	Heat credit (NG) ¢ kWh^{-1}	-2.34
Transportation Fuel (gasoline) Credit, $ y^{-1}	-12,480	Transportation Fuel (gasoline) Credit, ¢ kWh^{-1}	-22.72
Carbon credit, $ y^{-1}	0	Carbon credit, ¢ kWh^{-1}	0
System subsidy, $ y^{-1}	0	System subsidy, ¢ kWh^{-1}	0

CA average elec price, ¢ kWh^{-1}	16.8	LEC, ¢ kWh^{-1}	7.52
Annual cost for buying electricity from the grid at 16.8 cents per kWh, \$ y^{-1}	9,230	Annual electricity cost with tri-generation system, \$ y^{-1}	4,132

As shown in Table 6.7, capital cost, NG cost and gasoline credit are major components of LEC. The economics of installing and operating a tri-generation system is expected to be sensitive to these three cost components.

With heat and transportation credits (see Equation 4.12) based on the BAU reference system, the LEC of the 6.5 kW system is about 7.5 ¢ kWh^{-1}, which is 9.3 ¢ kWh^{-1} lower than the 16.8 ¢ kWh^{-1} electricity price. The annual electricity cost from the tri-generation system is \$4,132, while buying electricity from the grid is \$9,230. There is a 55% or \$5,098 decrease in the annual cost using the tri-generation system compared to the BAU reference system. In addition, there is a 25.8% or 19,658 kg reduction in annual CO_2 emission using the tri-generation system. Figure 6.10 presents a comparison of CO_2 emissions in the two cases.

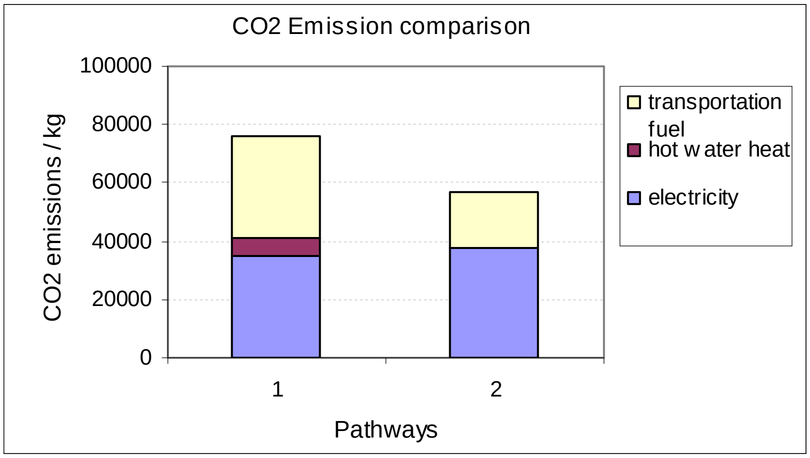

Fig. 6.10 CO_2 emission chart
Note: pathway 1- electricity + NG heat + gasoline (BAU); pathway 2- using a neighborhood tri-generation system with a hydrogen FCV

I have focused so far on estimating the LEC based on Equation 4.12. If I instead fix the electricity price (in this case study, I use the 16.8 ¢ kWh^{-1} grid electricity price), I can develop an analogous equation (Equation 4.13) for estimating the levelized hydrogen cost. Using this approach the model results show that a levelized hydrogen cost of \$4.06 kg^{-1} can be achieved using the tri-generation system given an electricity price of 16.8 ¢ kWh^{-1} and an NG price of \$1.09 $therm^{-1}$ (\$10.9 $MBTU^{-1}$). This is equivalent to a gasoline price of \$1.85 $gallon^{-1}$ assuming an FCV has a fuel economy of 55 miles per kg of H_2 and the gasoline car fuel economy is 25 mpg. In other words, holding other inputs constant, if the gasoline price reaches higher than \$1.85/gallon, the tri-generation system can be economically competitive with the BAU reference system of grid electricity, NG hot water heat and gasoline. This price is 40.7% lower than the \$3.12 $gallon^{-1}$ gasoline price in 2008. Furthermore, the hydrogen cost of \$4.06 kg^{-1} is highly competitive with purchasing hydrogen from an early hydrogen station (some research estimates that it can cost \$13-77 kg^{-1} from an early hydrogen station) [5]. In Section 6.3.2, the conventional gasoline vehicle will be replaced with an HEV to see how the model results would change.

6.3.2 Sensitivity analysis

From Table 6.7 we see that the major components determining the LEC are the system capital cost, NG cost, and transportation fuel cost. The HTS model allows us to evaluate the impact of uncertainty in capital cost and energy prices; it also allows us to 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. HEVs have gained some acceptance among consumers in the past few years. Overall HEVs have better fuel economy than conventional gasoline vehicles. The HTS model enables us to evaluate the impact of replacing the conventional gasoline vehicle in the base case with a vehicle that has better fuel economy such as an HEV.

To test the robustness of our results and address the uncertainty in capital cost and energy prices, I conducted a sensitivity analysis around the base case described in Tables 6.5 and 6.6. 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. I also evaluate the impact of replacing the conventional gasoline vehicle in the base case with a higher fuel economy gasoline vehicle such as an HEV. Sensitivity analysis results are summarized in Figure 6.11 and Table 6.8. In each case, it is informative and interesting to compare the cost of electricity of adopting the tri-generation system with the price of grid electricity (16.8 ¢ kWh^{-1}).

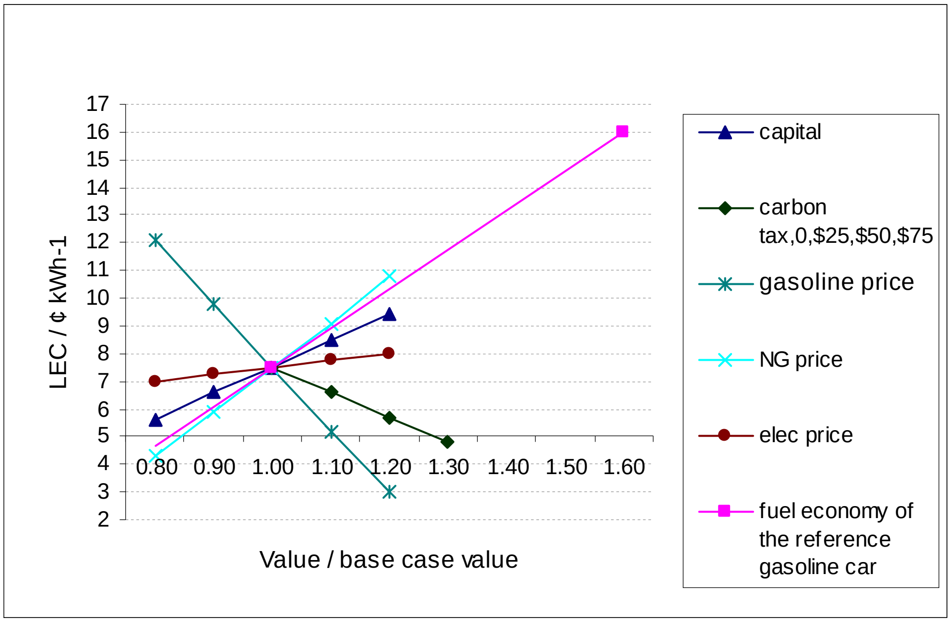

Fig. 6.11 The sensitivity of the LEC to capital cost, energy prices, carbon tax, and fuel economy of the reference gasoline car (shown for the 25 mpg base case and a 40 mpg HEV)

Table 6.8

The Sensitivity of LEC to capital cost, energy prices, carbon tax, and fuel economy of reference gasoline car

	20% decrease	10% decrease	base case	10% increase	20% increase	40% increase	60% increase
value/base case value	0.80	0.90	1.00	1.10	1.20	1.40	1.60
LEC with changes in capital cost, ¢ kWh^{-1}	5.6	6.6	7.5	8.5	9.4		
LEC perc change	-25.3%	-12.0%	0.0%	13.3%	25.3%		
elec price, ¢ kWh^{-1}	16.8	16.8	16.8	16.8	16.8		

LEC-elec price, ¢ kWh^{-1}	-11.20	-10.20	-9.30	-8.30	-7.40

LEC with changes in gasoline price, ¢ kWh^{-1}	12.1	9.8	7.5	5.2	3
LEC perc change	61.3%	30.7%	0.0%	-30.7%	-60.0%
elec price, ¢ kWh^{-1}	16.8	16.8	16.8	16.8	16.8
LEC-elec price, ¢ kWh^{-1}	-4.70	-7.00	-9.30	-11.60	-13.80

LEC with changes in NG price, ¢ kWh^{-1}	4.3	5.9	7.5	9.1	10.8
LEC perc change	-42.7%	-21.3%	0.0%	21.3%	44.0%
elec price, ¢ kWh^{-1}	16.8	16.8	16.8	16.8	16.8
LEC-elec price, ¢ kWh^{-1}	-12.50	-10.90	-9.30	-7.70	-6.00

LEC with changes in Elec price, ¢ kWh^{-1}	7	7.3	7.5	7.8	8
LEC perc change	-6.7%	-2.7%	0.0%	4.0%	6.7%
elec price, ¢ kWh^{-1}	13.44	15.12	16.8	18.48	20.16
LEC-elec price, ¢ kWh^{-1}	-6.44	-7.82	-9.3	-10.68	-12.16

LEC with changes in fuel economy of the gasoline vehicle,¢ kWh^{-1}	7.5			14	16
LEC percent change	0.0%			86.7%	113.3%
elec price, ¢ kWh^{-1}	16.8			16.8	16.8
LEC-elec price, ¢ kWh^{-1}	-9.30			-2.80	-0.80

LEC with Carbon tax (0, \$25, \$50, \$75),¢ kWh^{-1}	7.5	6.6	5.7	4.8	
LEC perc change	0.0%	-12.0%	-24.0%	-36.0%	
elec price, ¢ kWh^{-1}	16.8	16.8	16.8	16.8	
LEC-elec price, ¢ kWh^{-1}	-9.30	-10.20	-11.10	-12.00	

As shown in Figure 6.11 and Table 6.8, changes in system capital cost have significant impact on the LEC and economic performance of tri-generation systems. A 10% and 20% reduction in total system capital cost results in a 12% (0.9 ¢ kWh^{-1}) and 25.3% decrease (1.9 ¢ kWh^{-1}) in LEC, respectively. A 10% and 20% increase in total system capital cost leads to a 13.3% (1 ¢ kWh^{-1}) and 25.3% (1.9 ¢ kWh^{-1}) increase in LEC, respectively. A 20% increase in the base case system capital cost leads to a \$42,193 system capital cost, and with this increase in system capital cost the LEC is still 7.4 ¢ kWh^{-1} lower than the 16.8 ¢ kWh^{-1} grid electricity price.

A 10% and 20% decrease in gasoline price results in a 30.7% (2.3 ¢ kWh^{-1}) and 61.3% (4.6 ¢ kWh^{-1}) increase in LEC. Lower gasoline price allows lower transportation credit in Equation 4.12, and thus decrease the competitiveness of a tri-generation system. A higher gasoline price allows higher transportation credit in Equation 4.12 and improves the economic performance 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 a 30.7% (2.3 ¢ kWh^{-1}) and 60% (4.5 ¢ kWh^{-1}) decrease in LEC, respectively.

A 10% and 20% increase in NG price leads to a 21.3% (1.6 ¢ kWh^{-1}) and 44% (3.3 ¢ kWh^{-1}) increase in LEC, respectively. Increase in NG price increases the operation cost (by increasing the feedstock cost) of tri-generation systems and thus decrease the competitiveness of tri-generation systems. However, even with a 20% increase in NG price, the tri-generation system is still cheaper than the base case. A 10% and 20% decrease in NG price leads to a 21.3% (1.6 ¢ kWh^{-1}) and 42.7% (3.2 ¢ kWh^{-1}) decrease in LEC, respectively. Decrease in NG price reduces the operation cost of tri-generation systems and thus improves the economic performance of tri-generation systems.

Changes in electricity price do not lead to significant changes in LEC. As can be seen in Equation 4.12, increase in electricity price does not increase the operating cost of tri-generation systems significantly because the amount of electricity purchased is relatively small. However, the economic performance of tri-generation systems is still sensitive to electricity price, since what matters is the difference between LEC and electricity price. Although LEC does not change significantly with changes in electricity price, the changes in electricity price make the difference between LEC and electricity price vary significantly.

A 20% increase in electricity price results in a 6.7% (0.5 ¢ kWh^{-1}) increase in LEC; the resulting LEC is 8 ¢ kWh^{-1}, which is 12.2 ¢/kWh lower than the 20.2 ¢ kWh^{-1}

grid electricity price. A 10% increase in electricity price results in a 4% (0.3 ¢ kWh^{-1}) increase in LEC; the resulting LEC is 7.8 ¢ kWh^{-1}, which is 10.7 ¢ kWh^{-1} lower than the 18.5 ¢ kWh^{-1} grid electricity price. Increase in electricity price increases the competitiveness of a tri-generation system by making purchasing grid electricity more expensive.

A 20% decrease in electricity price results in a 6.7% (0.5 ¢ kWh^{-1}) decrease in LEC; the resulting LEC is 7 ¢ kWh^{-1}, which is 6.4 ¢ kWh^{-1} lower than the 13.4 ¢ kWh^{-1} grid electricity price. A 10% decrease in electricity results in a 2.7% (0.2 ¢ kWh^{-1}) decrease in LEC; the resulting LEC is 7.3 ¢ kWh^{-1}, which is 7.8 ¢ kWh^{-1} lower than the 15.1 ¢ kWh^{-1} grid electricity price. Decrease in electricity price decreases the competitiveness of a tri-generation system by making purchasing grid electricity less expensive.

Replacing the conventional gasoline vehicle in the base case with a more efficient gasoline vehicle significantly changes the economic performance of a tri-generation system. For example, if I assume a gasoline vehicle with a fuel economy of 35 mpg (this is 1.4 times the base case value and meets the 2020 CAFE standard), the resulting LEC is 14 ¢ kWh^{-1}, which is 6.48 ¢ kWh^{-1} higher than that of the base case (7.52 ¢ kWh^{-1}) and 2.8 ¢ kWh^{-1} lower than the 16.8 ¢ kWh^{-1} grid electricity price. The annual CO_2 emission reduction decreases from 25.8% (19,658 kg, base case) to 14.5% (9,601 kg). If I consider a gasoline hybrid vehicle with a fuel economy of 40 mpg (1.6 times the base case value), the resulting LEC is 16 ¢ kWh^{-1}, which is 8.48 ¢ kWh^{-1} higher than that of the base case (7.52 ¢ kWh^{-1}) and 0.8 ¢ kWh^{-1} lower than the 16.8 ¢ kWh^{-1} grid electricity price. The annual CO_2 emission reduction decreases from 25.8% (19,658 kg, base case) to 10.2%

(6,459 kg, with a 40mpg gasoline hybrid vehicle). Nevertheless, using tri-generation is still slightly at a lower cost than using grid electricity, NG hot water heat, and gasoline for an HEV.

A Carbon tax has positive impact on the economic performance of a tri-generation system, and the significance of the impact depends on the level of taxation. A \$25, \$50, and \$75 per metric tonne of CO_2 emission carbon tax results in a 12% (0.9 ¢ kWh^{-1}), 24% (1.8 ¢ kWh^{-1}), and 36% (2.7 ¢ kWh^{-1}) decrease in the LEC, respectively.

The simulation results so far demonstrate that the tri-generation system is economically competitive with the BAU reference system (grid electricity, NG hot water heat, and gasoline) without any credits, i.e., feebate or tax incentive, for all cases of sensitivity analysis. Therefore, I did not conduct separate analysis on the impact of credits on the LEC and economic performance of tri-generation systems in this chapter. Nevertheless, the sensitivity analysis on capital cost can provide some insight into how credits impact the economic performance of tri-generation systems. For instance, a 10% and 20% reduction in capital cost is equivalent to a \$ 3,516 and \$ 7,032 credit, respectively.

6.4 Chapter Summary

In this chapter, the interdisciplinary framework and the HTS model are applied to evaluate the design, and technical, economic, and environmental performances of a neighborhood tri-generation system. The system is designed to serve a 10-household multi-family residence.

With the representative annual energy consumption data and historical energy prices for this area or a close area, the optimal FC sub-system size of the neighborhood tri-generation system is 6.5 kW, and the corresponding LEC is about 7.5 ¢ kWh^{-1}. The LEC shows low sensitivity to the FC sub-system size around a broad minimum centered at 6.5 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 1%. Within the ranges tested, the optimal FC sub-system size is less sensitive to gasoline price and capital cost, and quite sensitive to NG and electricity price. The sensitivity to NG and electricity price is not expected to be a big concern to manufacturers and consumers since the LEC shows low sensitivity to FC sub-system size around a broad minimum centered at 6.5 kW.

An assessment of the optimal size (6.5 kW) tri-generation system shows that neighborhood tri-generation is more competitive than the base case of the BAU reference system (grid electricity, NG hot water heat, and gasoline). The LEC of the 6.5 kW system is about 9.3 ¢ kWh^{-1} lower than the 16.8 ¢ kWh^{-1} grid electricity price. There is a 55% or \$5,098 decrease in the annual cost using tri-generation systems compared to the BAU reference system. In addition, there is a 25.8% or 19,658 kg reduction in annual CO_2 emission using a tri-generation system.

Neighborhood tri-generation is also more competitive than the projected reference system (grid electricity, NG hot water heat, and purchasing hydrogen from an early public station). A levelized hydrogen cost of \$4.06 kg^{-1} can be achieved, which is equivalent to a gasoline price of \$1.85 $gallon^{-1}$. The hydrogen cost is highly competitive with the hydrogen cost from an early public station; some research estimates that it can cost \$13-77 kg^{-1} from an early hydrogen station.

Sensitivity analyses show that capital cost and energy prices have significant impacts on the LEC and economic performance of tri-generation systems. Specifically, the LEC is most sensitive to gasoline price, followed by NG price, electricity price, and capital cost.

Fuel economy of the vehicle in the BAU reference system significantly impacts the economic competitiveness of tri-generation systems in relation to the base case of the BAU reference system. Replacing the conventional gasoline vehicle (with a fuel economy of 25 mpg) in the base case with a 40 mpg HEV results in a LEC of 16 ¢ kWh^{-1}, which is 8.48 ¢ kWh^{-1} higher than the LEC of the base case of the BAU reference system, and 0.8 ¢ kWh^{-1} lower than the 16.8 ¢ kWh^{-1} grid electricity price. The annual CO_2 emission reduction decreases from 25.8% (base case) to 10.2% (with an HEV). Nevertheless, using tri-generation is still slightly at lower cost than the BAU reference system with an HEV.

A carbon tax has positive impact on the economic performance of a tri-generation system, but the significance of the impact depends on the level of taxation. A carbon tax of \$25, \$50, and \$75 per metric tonne of CO_2 emission results in a 12% (0.9 ¢ kWh^{-1}), 24% (1.8 ¢ kWh^{-1}), and 36% (2.7 ¢ kWh^{-1}) decrease in the LEC, respectively.

The simulation results in this study indicate that a neighborhood tri-generation system improves the economics of providing the three energy products for the households compared with the two alternatives studied in this chapter: the BAU reference system, and the projected reference system.

Replacing the conventional gasoline vehicle in the BAU reference system with gasoline vehicle with better fuel economy significantly decreases the competitiveness of a neighborhood tri-generation system, although using the tri-generation system (with an FCV) is still slightly at lower cost than the BAU reference system even with an 40 mpg HEV.

The small capacity of the neighborhood tri-generation system (relative to a public hydrogen station) and the valuable co-products helps address the low utilization problem of hydrogen infrastructure while hydrogen vehicle demand is low. Compared with the home tri-generation system assessed in Chapter 5, the economy of scale improves the economic performance of the neighborhood tri-generation system.

Chapter 7: Discussion of Other Issues

In addition to the simulation results, other considerations might impact the viability of tri-generation systems, but are not quantified explicitly in our analysis. Some of these considerations are summarized as follows.

1. 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. They also give consumers more control on power supply by allowing other feedstocks such as bio-gas. The discussion on other distribution benefits such as the liberalization of electricity markets, and reliability and power quality can be readily found in the literature [74-76].
2. The small capacity of home and neighborhood tri-generation systems (relative to a public hydrogen station) make it possible to provide better hydrogen fuel availability to consumers with lower life cycle cost while hydrogen demand is low. This study makes the comparison based on a single system from a consumer's perspective. In future research, a direct comparison of thousands of tri-generation systems with a regional hydrogen station network plan can be done.
3. The economic viability of tri-generation systems depends on regional conditions and energy prices. Our analysis used electricity consumption data and energy prices for Northern California area. For areas with different climates and NG to electricity price ratio, the results may differ. How the difference in energy demand profiles would change the economic and

environmental performances of tri-generation systems is not quantified in this research due to limited data availability for the time being.

4. NG fueled home and neighborhood tri-generation systems offer modest reductions in CO_2 emissions (21% and 25.8% for home and neighborhood tri-generation systems, respectively) compared to the BAU reference system (grid electricity, NG hot water heat, and gasoline used in a 25 mpg car). Ultimately, using renewable energy sources for home and neighborhood tri-generation systems could lead to near-zero CO_2 emissions. I did not consider renewable feedstocks in this analysis, but relied on NG as feedstock, which is the most likely option during early pre-commercial introduction of FCVs. However, renewable feedstocks such as bio-methane are potential feedstocks for tri-generation systems, and the attractive potential benefits of using renewable feedstocks for tri-generation systems justifies further investigation.
5. Identifying the best business model is essential to the commercial success of new technologies. This is especially true for tri-generation technologies since the energy products of the technologies are traditionally provided by different sectors: utility and transportation. Although home and neighborhood tri-generation systems use similar technologies, the business model for the two systems can be very different. A home tri-generation system can be simply owned and operated by individual home owners, while the ownership and operation of a neighborhood tri-generation system can be much more complicated. Below are some important questions associated with exploring a viable business model for a neighborhood tri-generation system:

1) Who will most likely invest in and own the neighborhood tri-generation systems?
2) Who will operate and maintain the systems?
3) Who will bill consumers? How are the consumers charged with their energy consumptions?

Utility companies, property owners and managers, homeowner association (HOA) boards (the governing bodies of most condos), and third party companies all can be potential owners and operators of a neighborhood tri-generation system. Whoever owns and operates the tri-generation system needs to find a convenient way to bill the consumers to collect returns and profits to their investment.

Tri-generation technologies also raise some policy and regulation questions. Currently, the utility industry and transportation energy industry are regulated differently in terms of tax, subsidy, and rate of return. Tri-generation systems simultaneously produce the three energy products, which are provided by utility industry and transportation energy industry. Policy makers need to explore the most cost effective way to accommodate the need for these technologies to succeed commercially. In addition, tri-generation system involves producing and storing hydrogen on site at the residential residences; new safety codes and regulations need to be designed to ensure safety without imposing unnecessary cost and burden to the industry and consumers.

Chapter 8: Conclusions and Future Research

8.1 Summary and Conclusions

While much research has been done on hydrogen infrastructure development, most has focused on the development of a network of large public hydrogen stations, similar to the conventional network of gasoline stations. Few research projects, if any, have analyzed distributed, small volume refueling methods such as home and neighborhood refueling methods investigated in this study. These small volume refueling methods may be required to refuel FCVs in the near term and may prove be a desirable long term refueling option for consumers. This study fills the gap by reviewing the role of distributed, small volume refueling methods in the development of fuel infrastructure for motor vehicles and by providing analytical tools to analyze these refueling methods in a systematic way.

I first presented a historical review and comparison of home and neighborhood refueling methods for a wide range of motor vehicles. Analytical tools including an interdisciplinary framework and engineering /economic model (the HTS model) are then developed for the detailed assessment of tri-generation systems for home and neighborhood refueling. The consumer’s preferences and WTP[17] for home and neighborhood refueling systems along with the environmental cost were discussed and incorporated into the HTS model.

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[17] In this work, consumer' WTP for home refueling is drawn from very limited literature because little work has been done in this area. Better determining WTP is left for future work.

I applied the analytical tools to a range of case studies, which can be grouped into two categories: home refueling tri-generation system case studies for single family residences (both slow and fast refueling cases), and neighborhood refueling tri-generation system case studies for multi-family residences. In each category, I explored the optimal design of tri-generation systems, and evaluated and compared the technical, economic, and environmental performances of tri-generation systems with two alternatives: the BAU reference system, in which consumers purchase grid electricity, NG hot water heat, and gasoline fuel; and the projected reference system, in which consumers purchase grid electricity, NG hot water heat, and hydrogen fuel from an early public station.

The optimal home and neighborhood tri-generation system sizes are relatively small-scale. The optimal FC sub-system size is 1.9 kW for a home tri-generation system, and 6.5 kW for a neighborhood tri-generation system serving 10 households.

The optimal FC sub-system size is insensitive to gasoline price, relatively sensitive to capital cost, and quite sensitive to the NG and electricity price, for both home and neighborhood tri-generation cases. The sensitivity of the optimal FC sub-system size to the NG and electricity price is not expected to be a big concern to manufacturers and consumers since the LEC (or electricity cost) shows low sensitivity to FC sub-system size around a broad minimum centered at 1.9 kW and 6.5 kW for home and neighborhood tri-generation systems, respectively. Changing the FC sub-system size by 1 kW increases the electricity cost by less than 2%.

Lower NG price and higher electricity price result in shorter payback periods for the NG fueled tri-generation systems.

Home tri-generation is generally a more expensive option than the BAU reference system. With the base case assumptions, the LEC with home tri-generation is about 2.6 ¢ kWh^{-1} to 3.8 ¢ kWh^{-1} higher than the 16.8 ¢ kWh^{-1} electricity price. The economic performance is significantly improved for the neighborhood tri-generation cases. Simulation results show that the neighborhood tri-generation system is more economically competitive than the BAU reference system. With the base case assumptions, the LEC of a 6.5 kW tri-generation system is about 9.3 ¢ kWh^{-1} lower than the electricity price.

Using the tri-generation system generates less CO_2 emission compared with the BAU reference system. There is a 20.52% and 25.8% reduction in annual CO_2 emission using the home and neighborhood tri-generation system, respectively.

Both home and neighborhood tri-generation systems are more economically competitive than the projected reference system (grid electricity, NG hot water heat, and hydrogen fuel from an early public station). A levelized hydrogen cost of \$7.95 kg^{-1} is achieved for home tri-generation systems, which is equivalent to a gasoline price of \$3.61 $gallon^{-1}$. A levelized hydrogen cost of \$4.06 kg^{-1} is achieved for neighborhood tri-generation systems, which is equivalent to a gasoline price of \$1.85 $gallon^{-1}$. The levelized hydrogen costs are both highly competitive with the hydrogen cost from an early public hydrogen refueling station (recent research suggests that hydrogen can cost \$13-\$77 per kg from an early, underutilized station).

Sensitivity analyses show that credits (such as tax credit and feebate), capital cost, and energy prices have a significant impact on the LEC and economic performance of home and neighborhood tri-generation systems. For home tri-generation systems, the

LEC and the economic performance is most sensitive to system capital cost, followed by NG price, electricity price, and gasoline price. For neighborhood tri-generation systems, the LEC is most sensitive to gasoline price, followed by NG price, electricity price, and capital cost.

The sensitivity of LEC to system capital cost and energy prices has the potential to make home tri-generation systems economically competitive with the BAU reference system. For example, a 14% reduction in capital cost, a $3,000 credit, or a 20% increase in gasoline price could enable the home tri-generation system to economically compete with the BAU reference system. The results suggest that credits and policies could play an important role in accelerating the adoption and commercialization of home tri-generation systems. Policies that may offer such incentives include the Alternative Fuel Infrastructure Tax Credit (federal level), Hydrogen Fuel Excise Tax Credit (federal level) [77], and Alternative Fuel and Vehicle Research and Development Incentives (state level, California) [78].

Carbon taxes have positive impact on the economic performance of the tri-generation system, but the significance of the impact depends on the level of taxation. A carbon tax of $50 per metric tonne of CO_2 emission results in a 5.6% and 24% decrease in the LEC for the home and neighborhood tri-generation systems, respectively.

Fuel economy of the vehicle in the BAU reference system significantly impacts the relative economic and environmental performance of the neighborhood tri-generation system to the BAU reference system. Replacing the conventional gasoline vehicle in the base case of the BAU reference system with an HEV (with a fuel economy of 40 mpg) results in a 8.48 ¢ kWh^{-1} increase in the LEC of the neighborhood tri-generation system .

Nevertheless, using the neighborhood tri-generation system is still slightly at lower cost than the BAU reference system with an HEV. The annual CO_2 emission reduction decreases from 25.8% (base case) to 10.2% (with an HEV).

Overall tri-generation for home and neighborhood refueling has the potential to be included in hydrogen infrastructure plans or portfolio infrastructure solutions in California and other states or countries. It is economically competitive with early public stations for fueling hydrogen cars. The small capacity of the home and neighborhood tri-generation systems (relative to a public hydrogen station) and the valuable co-products helps address the low utilization problem of hydrogen infrastructure while hydrogen vehicle demand is low. In addition, although home tri-generation systems are difficult to compete economically with the BAU reference system unless capital costs are reduced, or energy prices change, neighborhood tri-generation systems offer better economic performance than the BAU reference system.

8.2 Contributions and Future Research

This dissertation research investigates distributed, small volume refueling methods in contrast to most prior research on hydrogen infrastructure development that focused on the development of a network for large hydrogen stations. These small volume methods such as home and neighborhood refueling methods may be required to refuel FCVs in the near term and may be a desirable long term refueling option for consumers. By doing so, this study fills the gap in the research on hydrogen infrastructure development.

This study provides a review and comparison of home and neighborhood refueling methods for a wide range of motor vehicles, which helps us better understand the role of distributed, small volume refueling methods in the development of fuel infrastructure for motor vehicles including FCVs.

This study provides analytical tools including the interdisciplinary framework and HTS model to analyze tri-generation systems and similar energy systems in a systematic way. The consumer's preferences structure and WTP for home and neighborhood refueling systems are considered and incorporated into the interdisciplinary framework and modeling process.

This study conducted case studies of adopting home and neighborhood tri-generation systems using the HTS model and real world energy demand data and energy prices. The optimal design of tri-generation systems was explored. The technical, economic, and environmental performances of the tri-generation systems were evaluated and compared with the conventional technologies and other early options for providing hydrogen fuel. The industry, including automobile companies, utility companies, and fuel cell system developers will benefit from the information this study provides, which will assist them in decision-making and developing better marketing strategies. This study also provides government agencies with independent assessment of tri-generation systems for policy analysis and design, which is currently in great need. Furthermore, this study provides third party information to consumers about the feasibility, strength, and costs of adopting these systems.

There are several areas or questions that might impact the viability of tri-generation systems but are not quantified in this research. In future research, they can be investigated in great detail.

1. The simulation in this study shows that the small capacity of home and neighborhood tri-generation systems (relative to a public hydrogen station) has the potential to provide better hydrogen fuel availability to consumers with less life cycle cost while hydrogen demand is low. This study makes the comparison based on a single system from a consumer's perspective. In future research, a direct quantitative comparison of thousands of distributed tri-generation systems with a regional hydrogen station network serving one geographic area such as Southern California (both should offer the same level of fuel availability when hydrogen vehicle demand is low) from an investment perspective would be informative and have important policy implications.
2. The economic and environmental performances of tri-generation systems may depend on regional conditions. Our analysis used data for northern California. In future research, case studies can be conducted for regions with significantly different energy demand profiles to see how the performance of tri-generation systems varies with demand profiles.
3. NG fueled home and neighborhood tri-generation systems still rely on fossil fuels and offer only modest reductions in CO_2 emissions (21% and 25.8% for home and neighborhood tri-generation systems, respectively) compared to the BAU reference system. Only tri-generation systems using renewable energy sources could lead to near-zero CO_2 emissions. In future analysis, it is

important to conduct case studies of tri-generation systems using renewable feedstocks such as bio-methane.

4. Unlike a home tri-generation system, neighborhood tri-generation systems normally are not owned and operated by individual home owners. The ownership and operation of a neighborhood tri-generation system can be complicated. Utility companies, property owners and managers, homeowner association (HOA) boards (the governing bodies of most condos), and third party companies all can be potential owners and operators of a neighborhood tri-generation system. Exploring a viable business model for a neighborhood tri-generation system would be essential to the commercial success of neighborhood tri-generation systems and imperative in future research.

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