Technical Analysis of the Hydrogen Energy Station Concept

Phase I Report

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Executive Summary

Due to the growing interest in establishing a domestic hydrogen infrastructure, several hydrogen-fueling stations already have been established around the country as demonstration units. While these stations help build familiarity with hydrogen fuel in their respective communities, hydrogen vehicles are still several years from mass production. This limited number of hydrogen vehicles translates to a limited demand for hydrogen fuel, a significant hurdle for the near-term establishment of commercially viable hydrogen fueling stations.

By incorporating a fuel cell and cogeneration system with a hydrogen fueling station, the resulting “energy station” can compensate for low hydrogen demand by providing both hydrogen dispensing and combined heat and power (CHP) generation. The electrical power generated by the energy station can be fed back into the power grid or a nearby facility, which in turn helps offset station costs. Hydrogen production capacity not used by vehicles can be used to support building heat and power loads. In this way, an energy station can experience greater station utility while more rapidly recovering capital costs, providing an increased market potential relative to a hydrogen fueling station.

At an energy station, hydrogen is generated on-site. Part of the hydrogen is used for vehicle refueling and part of the hydrogen is consumed by a fuel cell. As the fuel cell generates electricity and sends it to the power grid, excess heat is reclaimed through a cogeneration system for use in a nearby facility. Both the electrical generation and heat reclamation serve to offset the cost of purchasing the equivalent amount of energy for nearby facilities and the energy station itself.

This two-phase project assessed the costs and feasibility of developing a hydrogen vehicle fueling station in conjunction with electricity and cogenerative heat generation for nearby Federal buildings. In order to determine which system configurations and operational patterns would be most viable for an energy station, TIAX developed several criteria for selecting a representative set of technology configurations. TIAX applied these criteria to all possible technology configurations to determine an optimized set for further analysis, as shown in Table ES-1.

This analysis also considered potential energy station operational scenarios and their impact upon hydrogen and power production. For example, an energy station with a 50-kWe reformer could generate enough hydrogen to serve up to 12 vehicles/day (at 5 kg/fill) or generate up to 1,200 kWh/day, as shown in Figure ES-1.

Buildings that would be well suited for an energy station would utilize both the thermal and electrical output of the station. Optimizing the generation and utilization of thermal energy, hydrogen, and electricity requires a detailed look at the energy transfer within the energy station and the transfer between the station and nearby facilities. TIAX selected the Baseline configuration given in Table ES-1 for an initial analysis of the energy and mass transfer expected from an operating energy station. The remaining configurations will be analyzed further in the second phase of this program.

Table ES-1. Representative Energy Station System Component Configurations

System Attributes	Major Components
Configuration I (high-pressure Steam-methane Reformer [SMR])	Air Compressor (high pressure), SMR, Pressure-Swing Absorption (PSA), Direct-Hydrogen Fuel Cell
Configuration II (low-pressure SMR)	Air Compressor (low pressure), SMR, PSA, Direct-Hydrogen Fuel Cell
Configuration III	Compressor, SMR, Preferential Oxidizer (PrOx), Reformate Fuel Cell, PSA
Configuration IV	Autothermal Reformer (ATR), PrOx, Reformate Fuel Cell, PSA
Configuration V	Air Compressor, ATR, PSA, Direct-Hydrogen Fuel Cell

Figure ES-1. Number of Vehicles Served by a 50 kWhe Reformer Given Daily Fuel Cell Power Output

In an effort to identify the ideal facilities for the near-term placement of hydrogen energy stations, a list of characteristics that would be ideal for a pilot project facility were developed, as shown in Figure ES-2. These characteristics formed the initial criteria by which the facility options were determined. Most, if not all, of the criteria needed to be met for an ideal energy station. Given that this program sought to identify a federal facility for siting a hydrogen energy station, initial contacts were made with local representatives of the General Services Administration (GSA) and the U.S. Department of Energy (DOE) to gain more information about potential sites. From this survey a short list of potential host sites was developed.

Figure ES-2. A Step-by-Step Process was used to Determine the Characteristics of Facilities that have High Potential for Use of an Energy Station

Further investigation is needed to assess the specific design requirements, comparative costs, emissions, and operation of these representative energy station configurations. Using the representative energy station configurations outlined in this phase, the utilization costs and output should be determined for target host sites. Additionally, the potential participants in developing such a system should be contacted in order to ascertain their interest. Finally, an analysis of the different types of barriers and obstacles facing hydrogen infrastructure development is needed along with an assessment of the extent to which the federal government will need to support these efforts.

1. Introduction

Over the past decades, the “hydrogen economy” has been the subject of numerous visionary discussions. The potential benefits of hydrogen use as a vehicle fuel, for stationary power generation and heating, and the possible formation of hydrogen from renewable resources have been described. At the same time, most accept that significant challenges remain to realize a hydrogen economy, especially when considering the transition period needed to develop a hydrogen-fueling infrastructure.

In an attempt to address these challenges, TIAX developed a hydrogen-fueling concept that integrates transportation and stationary uses of hydrogen with the aim of reducing cost and increasing market potential. By incorporating a fuel cell and cogeneration system into a hydrogen fueling station, the resulting “energy station” can compensate for low hydrogen demand by providing both hydrogen dispensing and combined heat and power (CHP) generation. This study examined the technical and economic feasibility of developing commercially viable energy stations, and the role that the government will need to play in this effort.

In addition to efficiency and cost benefits, co-locating hydrogen production with building cogeneration and on-site fuel cell power production may offer additional benefits. For example:

- Fuel cell systems have low emissions, if any, relative to other distributed generation options
- The capacity of the reformer and hydrogen storage systems could be optimized, as better load matching would be achievable and typical load profiles for the fueling station and for the buildings are often partially complementary
- Early application may be possible because the energy station concept is applicable to fleet and retail refueling settings, and this common application considerably reduces the technical risk for the entire system
- For early retail stations, the combination of hydrogen production and CHP could diminish the financial burden associated with low hydrogen sales during the first few years of operation, when few hydrogen-fueled vehicles are expected to be on the road

1.1 Hydrogen Future Act of 1996

The Hydrogen Future Act of 1996 directed the U.S. Department of Energy (DOE) to conduct a research, development, and demonstration (RD&D) program that would lead to the development of a hydrogen fuel infrastructure. The purpose of this technical analysis was to analyze the development of a hydrogen infrastructure for transportation concept that incorporated hydrogen fueling with the installation of 50 to 75 kW stationary fuel cell modules at Federal building sites. This analysis determined the costs, designs, and potential challenges for establishing an energy station that provides hydrogen fuel for both a fuel cell and a limited number of hydrogen powered vehicles, and provides the reclaimed waste heat and fuel cell electricity to a nearby facility.

1.2 Hydrogen Energy Station Requirements

Building viable hydrogen energy stations will require further efforts to reduce costs, comply with safety requirements, and develop equipment that is suitable for commercial applications. The issues surrounding each of these requirements are discussed in greater detail below.

1.2.1 Investment and Cost Risk

Current estimates show that the implementation of fuel cell vehicles will result in higher cost of mobility than with current vehicle technology. However, the magnitude of the cost risk varies as well as its nature and who bears it. For example, while a direct-hydrogen fueling option might result in the smallest premium for fuel cell vehicle cost and the least technology risk to vehicle manufacturers, it would likely require significant investments in fuel production and distribution infrastructure. This would expose fuel producers and distributors to considerable market risks with enormous investments. Integrating hydrogen production with power generation—thus creating “energy stations”—provides potential cost reductions, improved efficiency, and reduced risk.

1.2.2 Safety and Liability

The issues relating to the reliability and safety of hydrogen fueled vehicles include concerns about explosion risks, especially related to leaking vehicles in covered spaces (hydrogen accumulates on the ceiling, rather than the floor like gasoline). Local fire officials will need to become familiar with hydrogen vehicle requirements. On-site operators of the hydrogen energy station components, including those that refuel hydrogen vehicles, also will need to be aware of the safety concerns and the appropriate handling and operational procedures.

1.2.3 RD&D Priorities

Finally, the RD&D priorities for hydrogen fueling stations will depend considerably on the choice of fueling station technologies. Considering the large investments in RD&D that are required for a change of this magnitude, it would be inefficient, if not impossible, to develop all fueling system options to the required end state and then make a choice between them. Rather, the industry and government will have to bundle its resources. As the technology moves to market, this cooperation becomes even more important. If stakeholders are unsure whether or not the technology options they support will be adopted, they will be extremely unwilling to make the enormous investments needed to bring such hydrogen infrastructure technologies to market.

1.3 Analysis Needed for Advancement of Hydrogen Technologies

To successfully bring an energy station to market, energy station developers and manufacturers will need to understand the technical feasibility, commercialization, and cost issues of the fuel cell system, as well as the use of the fuel cell electricity and cogenerative heat in Federal buildings. Part of this project’s goal was to explore the different ways by which industry can be assisted in planning an energy station-based hydrogen infrastructure. As a result, TIAX included in this project an exploration of the opportunities for private/public partnerships. TIAX also included an initial assessment of the location and size of the fleet vehicles that would utilize this

type of hydrogen infrastructure, the cost and technical issues associated with the infrastructure's development, and the amount of the cost that would have to be provided by the federal government.

1.4 Study Approach

To carry out this analysis project as effectively as possible, TIAX structured a two-phase program that consisted of four tasks each for each phase, including one reporting task in each phase. The following subsections describe the project scope and methodology for the first phase of the project.

1.4.1 Scope of Work

The project included identifying potential energy station hosts as well as analyzing energy station configurations and their respective integration with buildings. Table 1-1 shows the Work Breakdown Structure (WBS) for the year's activities.

Table 1-1. Work Breakdown Structure

Task 1 — Analyze System Cost and Performance
1.1 Review reformer, hydrogen purification, and compressor technologies
1.2 Evaluate direct-hydrogen and reformat fuel cells
1.3 Assess reformer sizing options as related to fuel cell output
1.4 Evaluate different fuel cell power utilization options
1.5 Evaluate hydrogen storage and compression options
1.6 Integrate above analyses with vehicle fleet size and fueling needs
1.7 Select most promising (four to five) system options for detailed analysis
Task 2 — Assess Public/Private Fleet Size/Locations
2.1 Attend/Hold stakeholder workshops on Alternative Fuel Vehicle (AFV) fleet planning
2.2 Obtain California fleet projections from California Fuel Cell Partnership
2.3 Obtain fleet projections from current EPA AFV fleet operators
2.4 Research policy mandates for AFV fleets
Task 3 — Evaluate Building Integration
3.1 Determine available waste heat
3.2 Evaluate cogeneration heat potential uses in buildings
3.3 Analyze building thermal, hydrogen, and electric demand
Task 4 — Preliminary Reports
4.1 Interim reports summarizing year one milestones
4.2 Project tasks for year two
4.3 Presentation for annual peer review meeting

Task 1 — Analyze System Cost and Performance

The first task conducted under this project was to evaluate the cost, performance, and technical feasibility all of the competing technologies that could be utilized for the fuel cell and vehicle fueling system components. The goal of this initial, broad-based assessment is to select the most promising (four to five) system designs and technologies on the basis of this evaluation. The subsystems, components, and issues analyzed in Task 1 include: reformer technologies, hydrogen purification technologies, fuel cell hydrogen utilization, reformer sizing options, hydrogen storage and compression, and vehicle fleet size and fueling needs.

Task 2 — Assess Public and Private Fleet Characteristics

To complete this task, TIAX and Bevilacqua-Knight, Inc. collected data from governmental agencies and a representative group of fleets and associated facilities. Key sources of information for vehicle fleet size and location were the DOE EPA fleet administrators who indicated sparse reporting of current and projected AFV fleet practices; the General Services Administration, which is responsible for acquiring cars for the federal government; and Clean Cities coordinators who provided contact information for federal fleets. Finally, air quality and energy policies that will either directly or indirectly encourage hydrogen fleets were reviewed for their potential impacts.

Task 3 — Evaluate Building Integration

Using the results of Task 1 and a representative set of system designs and technologies selected for further analysis, the likely amounts and grades of waste heat that would be produced from the reformer and stack(s) were determined. With this information, cogenerative heat uses and technologies were researched and evaluated with respect to beneficial utilization or possibilities in a commercial/government building setting.

Task 4 — Preliminary Reports

Deliverables in the form of this preliminary report and a presentation for a peer review meeting were completed for the project. These summarized the milestones and accomplishments of the first year and project tasks for the second year of the project.

Proposed Work (Phase II)

Upon completion of the above tasks, TIAX will propose to continue the analysis and identification of energy station applications in Federal buildings. The tasks under this second phase include exploring specific public and private partnerships to support the establishment of a hydrogen energy station in a Federal facility. Also, under this second phase, TIAX will analyze the cost, emissions, and energy utilization benefits of integrated power and fueling, identify the key technology, cost, and public perception barriers to hydrogen use, and make recommendations for future development.

1.4.2 Methodology

System Analysis

A variety of integrated system designs and technologies are possible for hydrogen producing energy stations. In order to provide a detailed analysis of viable energy stations, the universe of possible system design and technology configurations was reduced to a representative sample of four integrated systems. The representative sample was determined by ranking the possible integrated configurations by cost, performance, and technical feasibility.

The top four representative energy station configurations were then analyzed under various operational scenarios. These scenarios considered various levels of hydrogen and electricity generation, hydrogen storage, and fleet vehicle hydrogen usage. These scenarios also considered the amount of waste heat utilized by a nearby building, and the time of day variations in fuel cell, reformer, storage, and vehicle refueling operations.

Using the operational analyses, a preliminary assessment of each representative station configuration was provided, highlighting the benefits and disadvantages of each. This analysis also indicated areas requiring further investigation.

Infrastructure and Partnership Development

It is well known that introducing new technology to the marketplace begins with testing among a focused group of participants. An energy station is no different. Although it could become a widespread technology, the early development of the energy station concept is best suited to types of fleets and facilities that would provide the least number and severity of hurdles. Federal facilities fit this requirement well due to the existing requirements for alternative fuel vehicles among their fleets and the willingness for government agencies to participate in government projects.

In order to identify federal facility partners, TIAX developed a list of criteria for potential sites. TIAX then enlisted BKi, a transportation consulting company, to develop a list of potential federal energy station sites using information from federal agencies and organizations. BKi narrowed the list by interviewing potential partners at these sites to determine if and how they fit the criteria.

A hydrogen-producing energy station reforms an input fuel to produce a feedstock for fuel cell operation.¹ The reformer output would also be purified, with the resultant hydrogen being stored for dispensing into hydrogen-fueled vehicles. The electrical power generated by the fuel cell and/or the residual heat from the system processes may be used to support energy station and nearby building power and heat loads. Figure 2-1 shows the various major components that make up a hydrogen energy station.

In order to develop a representative cost and energy output estimate for the energy station, a review of the candidate system technologies was performed. The sections below briefly describe the variety of technologies included in the representative scenarios.

2-1

2.1.1 Reformer Technologies

The technologies in Table 2-1 below encompass the variety of reformer systems that could be implemented in a hydrogen energy station. The trade-offs associated with using each of these technologies have been identified and are also presented in Table 2-1.

Table 2-1. Trade-off List for Reformer Technologies and Fuels

Technology	Trade-offs
Autothermal Reformer (ATR)	Lower hydrogen yield, projected higher volume production and lower cost, simpler to operate
Steam Reformer (SR)	Higher hydrogen yield, more complicated/expensive, low volume production
Fuels	Trade-offs
Natural Gas-fueled	Natural gas service widespread, offered to most buildings, requires reformer
Methanol-fueled, Ethanol-fueled	Requires shipments (unless produced onsite), may be possible to utilize direct-methanol fuel cell
LPG-fueled	Requires shipments, but may be appropriate if LPG already available, compression handled upon delivery, not utilization
Gasoline-, diesel-fueled	Requires shipments, unless already part of on-site fleet fueling supplies. May be able to use reformer technology being developed for vehicle market.

Autothermal Reformers

The autothermal reformer (ATR) system converts hydrocarbon fuels into hydrogen by reacting fuel, air, and steam over a catalyst. The ATR requires preheating in order to activate the catalyst and operate as a reformer. In order to preheat the system, an auxiliary burner, such as the tailgas burner (TGB) normally operating off of the pressure-swing absorption (PSA) system/fuel cell exhaust, burns the fuel, then passes the exhaust heat to the ATR. Once the reforming temperature is reached, the fuel is passed directly to the ATR for reforming. The ATR system is preferred for automotive on-board reforming and is anticipated that such systems will be mass-produced for reformer-based fuel cell vehicles.

Steam Reformers

The steam reformer (SR) requires a supply of superheated steam to generate hydrogen. The high temperatures are provided initially by burning the fuel in a TGB, as with the ATR system. Once the steam is at the reforming temperature, heat from the reforming process and PSA waste gas is used to generate additional steam.

Fuels: Methanol/Ethanol, Natural Gas, LPG, Gasoline/Diesel

Reformers may use methanol, ethanol, natural gas, liquefied petroleum gas (LPG—mainly propane), gasoline, or diesel to generate a hydrogen-fortified gaseous output. Natural gas most

likely would be provided to an energy station by connecting to utility gas service. Methanol, ethanol, natural gas (compressed or liquefied), LPG, gasoline, or diesel service could be provided by truck from off-site sources. Co-locating an energy station with other on-site facilities requiring the same input fuel (e.g., natural gas) could minimize the need for additional compression and/or storage infrastructure.

2.1.2 Fuel Cell Technologies

Direct-hydrogen fuel cells require that reformat output be purified, as carbon monoxide (CO) and other gases present in the reformer output will degrade fuel cell performance. However, direct-hydrogen fuel cells are more efficient than reformat-fueled fuel cells, thus requiring a smaller, less-expensive fuel cell for a given power rating. Reformat-fueled fuel cells do not require the same level of purification as a direct-hydrogen fuel cell, but still require a preferential oxidizer (PrOx) upstream of the fuel cell to oxidize most of the CO prior to reaching the fuel cell. Fuel cells produced for fuel cell vehicles (FCVs) are expected to be less expensive than stationary fuel cells due to economies of scale associated with large production volumes. Using FCV fuel cells in energy stations may reduce the expense of incorporating a fuel cell into the energy station system. These trade-offs are summarized in Table 2-2.

Table 2-2. Trade-off List for Fuel Cell Technologies

Technology	Trade-offs
Reformat-fueled Fuel Cell	Purification not needed for fuel cell (but needed for dispensing to vehicles), less efficient, waste gas useable for additional burn
Compressed Hydrogen Fuel Cell	Purification required, higher efficiency
Direct-hydrogen Vehicle fuel cell Used as a Stationary Fuel Cell	Large scale manufacturing anticipated, low cost, higher efficiency

2.1.3 Hydrogen Purification Technologies

The PSA system provides a means for separating the hydrogen from other gases coming out of the reformer. The PSA uses multiple stages to distill hydrogen from the reformer exit stream. The hydrogen is diverted to storage and/or use while PSA waste gases are passed to a TGB to generate additional heat for the rest of the system or to be vented outside the station. The PrO_x oxidizes the CO in the reformer output to avoid fuel cell performance degradation. Membrane filtration may also be used, but is more costly than using a PSA system of comparable throughput. These hydrogen purification technology trade-offs are summarized in Table 2-3.

Table 2-3. Trade-off List for Hydrogen Purification Technologies

Technology	Trade-offs
PSA	<ul style="list-style-type: none"> • Conventional technology for >100 kg/day scale • Requires high pressure (>10 atm) reformat gas, resulting hydrogen is at high pressure • Hydrogen yield (i.e. recovery) is much better for higher hydrogen concentrations (SR feed versus ATR feed). Hydrogen yield also depends on differential pressure, reformat composition, and system size (i.e. number and size of beds or membrane area).
Membrane Hydrogen Separation	<ul style="list-style-type: none"> • May have cost advantages over PSA for small-scale systems (<100 kg/day) • Requires high pressure (>10 atm) reformat gas. The main disadvantage of membranes for applications requiring hydrogen storage, is the resulting low - pressure hydrogen stream. • Hydrogen yield (i.e. recovery) is much better for higher hydrogen concentrations (SR feed versus ATR feed). Hydrogen yield also depends on differential pressure, reformat composition, and system size (i.e. number and size of beds or membrane area).
PrO _x	<ul style="list-style-type: none"> • Does not require high pressure feed gas • Enables entire reformer product stream to be fed to a fuel cell for stationary power. Further hydrogen separation is required for vehicle fueling. • Hydrogen is consumed along with CO (about 1 mole H₂ per mole CO)

2.1.4 Compression and Storage Technologies

Compressors are required to compress the hydrogen for storage. Typically, compressed hydrogen is stored at 5,000 to 6,000 psi, but may be stored at lower pressures to lower compressor costs and increase overall system efficiency, if space permits. If the reformer operates at an elevated pressure, then compressors may be required to maintain the proper inlet gas pressure for the natural gas and inlet air. Compressor-expanders may also be employed to use pressurized exhaust gases to compress the inlet air supply. In general, compressor cost will scale with increasing capacity and pressure level. These trade-offs are summarized in Table 2-4.

Table 2-4. Trade-off List for Compression and Storage Technologies

Technology	Trade-offs
Compressor/expander	More expensive, provides compression for incoming air
Blower	Less expensive, does not compress air
High-pressure Storage	More expensive (requires stronger compressors), allows greater flexibility of system operation, stores more hydrogen into smaller space
Staged Compression	More complex, allows for faster recharging of storage system, greater system efficiency and smaller high-pressure system
Single-pressure Storage	Simpler than staged compression, may not be as efficient and cost-effective as staged compression

2.2 Operational Configurations

To determine the station operational parameters, TIAX first determined potential fuel cell operational scenarios and reformer operational scenarios. The possible scenarios are described below followed by a description of the selected representative scenarios afterwards.

2.2.1 Evaluation of Hydrogen Storage and Compression Options

High-capacity Storage

High-capacity storage is appropriate for scenarios where the fuel cell regularly operates at loads requiring higher hydrogen feed rates than can be produced by the reformer. The larger capacity allows for longer periods of high-load fuel cell operation, such as during building load peak-shaving. This option also would allow for greater fluctuation in instantaneous hydrogen demand, and allow for production capacity growth over time from the station, the building, or the hydrogen vehicle fleet served by the station.

Low-capacity Storage

Low-capacity storage is appropriate for scenarios where the fuel cell most often operates at loads where the fuel cell hydrogen demand is about equal to or lower than the reformer hydrogen production rate. Excess hydrogen is stored in anticipation of small fluctuations in hydrogen demand. This approach is appropriate if the total hydrogen demand from the fuel cell and serviced hydrogen vehicles is fixed or well controlled.

High-pressure Storage (>5 kpsi)

High-pressure storage allows greater storage capacity on a mass basis due to increased hydrogen density. High-pressure storage also reduces the required storage space for a given mass of hydrogen. However, higher-pressure systems require more expensive higher-pressure compressors.

Single-pressure Storage

The single-pressure storage option would be appropriate for all configurations. It does not involve staging, and would occur at the highest pressure required to accommodate all systems.

Multi-stage Storage

Multi-stage or cascade storage would be appropriate for reformer systems that produce moderate-pressure hydrogen. Having two or more levels of storage would allow one reserve to be filled quickly at moderate pressure—potentially without the need for a compressor—while the remaining storage would be filled using a high-pressure compressor. Such a system would dispense hydrogen more efficiently by dispensing hydrogen from the moderate-pressure storage until the receiving tank reaches the moderate pressure, then dispensing hydrogen from the high-pressure storage. With part of the hydrogen storage maintained at moderate pressure, depleted reserves would be regenerated more quickly and the capacity requirements for high-pressure storage would be reduced.

Other Storage

Although other types of hydrogen storage are under development, such as metal hydride, and carbon nanotubes, this analysis only considered those technologies described above.

2.2.2 Evaluation of Reformer Operational and Sizing Options

Potential reformer operational modes include constant baseline, constant baseline with load following, on demand, and scheduled operation. These options are not necessarily exclusive and may be used in combination with other operational modes.

Constant Reformer Operation

Under this scenario, the reformer is operated at a constant load, providing hydrogen for fuel cell use when in operation, and generating hydrogen for storage when the fuel cell demand drops below reformer hydrogen output. Vehicles would be filled using stored hydrogen. Under the constant operation scenario, the reformer would be operated in one of the following modes:

- The reformer load is matched to the maximum anticipated fuel cell demand, generating excess hydrogen for storage when the fuel cell is not operating at maximum demand. If a vehicle refuels while the reformer and fuel cells are operating at maximum load, vehicle hydrogen will be supplied from storage.
- The reformer load is under-powered with respect to maximum fuel cell hydrogen demand. This would require the fuel cell to draw from stored hydrogen when fuel cell demand exceeds reformer output. When fuel cell load is lower than reformer output, the excess hydrogen is stored (see Figure 2-2).

Combined Baseline Load and Load-following Operation

Under this scenario, the reformer is operated at a load just over what is required to support the fuel cell during minimum electrical demand, and storing excess hydrogen. Under the combined baseline and load-following scenario, the reformer would be operated in one of the following modes:

- During peak electrical demand, the reformer increases its hydrogen production to match the increased demand from the fuel cell. In this case, vehicle refueling is supported by stored hydrogen from off-peak excess production (see Figure 2-3).
- Vehicle fueling hydrogen demand is matched by the reformer, if needed. In this case, the fuel cell would run off stored hydrogen from off-peak excess.
- Vehicle fueling hydrogen demand and fuel cell demands are matched by the reformer.
- The reformer also could be operated at a load lower than what is required to support fuel cell operation during maximum electrical demand. In this case, no excess hydrogen is generated. This would occur if the maximum electrical demand is not expected to be completely met by the fuel cell.

Figure 2-2. Example Constant-load Reformer and Building Load-following Fuel Cell Operational Scenario

Figure 2-3. Example Load-following Reformer System and Load-following Fuel Cell Operational Scenario

On-demand Reformer Operation

Under this scenario, the reformer is operated when hydrogen is needed for the fuel cell and/or vehicle refueling. When hydrogen is not needed by either system, the reformer shuts off. Under the on-demand operation scenario, the reformer would be operated in one of the following modes:

- Reformer follows the demand for the total system. The reformer would be sized to handle the maximum combined demand from the fuel cell and vehicle refueling system. Minimal hydrogen storage requirements—just enough to support fuel cell/refueling during reformer warm-up period.
- Reformer follows the demand from the fuel cell. Reformer is sized under the maximum fuel cell hydrogen demand level. Hydrogen demand above reformer capacity is met using stored hydrogen.
- Reformer follows the demand from the fuel cell. Reformer is sized to meet the maximum hydrogen demand from the fuel cell. In order to generate sufficient hydrogen for future vehicle refueling and to supplement the reformer output during the next start-up period, the reformer would generate excess hydrogen when in operation and/or continue to operate after the fuel cell shuts off. The reformer would generate enough hydrogen to fill the hydrogen storage system, then shut off. Would operate in absence of fuel cell demand if hydrogen storage drops below specified threshold (see Figure 2-4).

Figure 2-4. Example On-demand Reformer System and Peak-shaving Fuel Cell Operational Scenario

Timed Operation

Under this scenario, the reformer is operated during specific hours of the day. The reformer could be operated at a pre-set time duration and load, generating hydrogen for immediate use and/or storage. Under the timed operation scenario, the reformer would be operated in one of the following modes:

- During peak electrical demand, the reformer operates at a specific load to generate enough hydrogen for the fuel cell to partially offset grid power usage. Part of the hydrogen is diverted for storage to accommodate refueling vehicles.
- During peak electrical demand, the reformer operates to follow fuel cell hydrogen demand. Part of the hydrogen is diverted for storage to accommodate refueling vehicles.
- During specific non-peak hours, reformer generates sufficient hydrogen to support fuel cell operation and refueling demand during on-peak hours. All hydrogen is stored for on-peak use.
- During specific off-peak hours, reformer generates sufficient hydrogen to support baseline off-peak fuel cell load and create stored reserve for on-peak fuel cell operation and refueling.
- A combination of the above on-peak and off-peak operational modes (see Figure 2-5).

Figure 2-5. Example Timed Reformer System and Fuel Cell Operation Scenario

Reformer Sizing Options

In addition to the variety of possible reformer operational scenarios, various reformer power sizes are also possible. The minimum size requirements for the reformer will depend upon the magnitude of fuel cell demand, the timing of the demand, and the amount of hydrogen required for vehicle refueling. Reformer sizing should also consider future demand due to growth in the hydrogen vehicle population that would refuel at the energy station. Given that the hydrogen produced by the reformer may be used by either the energy station fuel cell or hydrogen vehicles, a reformer that supports mainly fuel cell operation in the first years of operation may later be used to support mainly hydrogen vehicles after the vehicle population has grown sufficiently. Figure 2-6 shows an example of this trade-off between fuel cell operation and hydrogen available for vehicle refueling for various reformer sizes.

Figure 2-6. Hydrogen Available for Station and Vehicle Use Given Fuel Cell Consumption and Various Reformer Loads

2.2.3 Evaluation of Different Fuel Cell Power Utilization Options

Fuel cell power utilization options include peak shaving, constant baseline load, scheduled operation, on demand operation, and load following. As with the reformer operation modes, these options are not necessarily exclusive – in some cases they may be used in combination.

Peak Shaving

Under this scenario, the power to be produced by the fuel cell during peak load hours (late morning through afternoon) will offset part of the building power load. Peak shaving lowers the

amount of electricity taken from the utility power grid during peak load hours, when electricity rates are highest. The fuel cell always will support the energy station power load, which may fluctuate depending upon the level of refueling activity and hydrogen generation/storage. Under the peak shaving scenario, the fuel cell would be operated in one of the following modes:

- Constant fuel cell power output during peak hours, providing a fixed electrical power level to the building and energy station, combined. Since the fuel cell output is fixed under this mode, when the energy station demand rises temporarily—such as during vehicle refueling—this would lead to a corresponding drop in the power level delivered to the building.
- Variable fuel cell power output during peak hours, providing constant power to the building and following the station electrical demand. Should the energy station demand fluctuate, the fuel cell could follow the change in demand so as to leave the power supply to the building constant. The power provided to the building should be selected such that the combined building power and station power demand does not exceed the power capacity of the fuel cell. If such a provision is too limiting with respect to desired building power supply, the station could be designed to curtail certain functions during peak shaving should combined station and building power demand reach the maximum fuel cell power capacity.
- Variable fuel cell power output during peak hours, following the combined building and station electrical load up to the capacity of the fuel cell. Under this mode, the fuel cell would need to be sized to accommodate the anticipated range of power demand. Otherwise, a power management algorithm would be needed to determine when to curtail energy station operation and/or reduce power supply to the building should the fuel cell reach its maximum power output.

Constant Baseline Load

Under this scenario, the fuel cell runs continuously at a constant rate to support a “baseline” load—a level at or below the minimum building power demand—in one of the following modes:

- Constant fuel cell power level below the minimum power requirement for the building, providing power for both the energy station and the building. If energy station power demand temporarily rises, the power delivered to the building drops proportionally to keep the fuel cell power delivery constant.
- Constant building power, variable fuel cell power would allow the fuel cell to follow the energy station load.

Scheduled Use

Under this scenario, the fuel cell would be operated certain fixed hours during the day. This scenario uses the same operational modes as the peak shaving scenario, except that the operational period could include off-peak hours.

On Demand

Under this scenario, the fuel cell is operated when needed by the energy station, and is not used during other times. The fuel cell may provide power to the building while providing power to the energy station, but never provides power to the building exclusively.

Load Following

Under this scenario, the fuel cell is operated continuously to support the building and energy station loads. As energy requirements fluctuate during the day, the fuel cell matches the electrical demand accordingly. The fuel cell meets the energy station electrical needs and part or all of the building electricity needs. If the fuel cell meets only part of the building electrical load, the fuel cell may meet that need at a fixed proportion of full demand.

2.2.4 Evaluation of Cogeneration Options

Excess heat from the energy station will be recovered for use in a nearby facility. The most significant source of waste heat generated by the energy station is contained in the fuel cell stack exhaust and heat rejection loops, followed by PSA waste heat and gases, waste heat and combustible gases rejected from the steam methane reformer, and additional waste heat produced by the compression of hydrogen for storage. Capturing this excess energy can be accomplished in various ways, as described below.

Fuel Cell Waste Heat

A heat exchanger placed in line with the fuel cell heat rejection loop and stack exhaust can reclaim a significant amount of waste heat that would be otherwise rejected to the atmosphere. This waste heat can then be transferred to a nearby facility for heating water.

PSA Waste Heat and Gases

If used, a PSA system would normally exhaust leftover combustible gases to a tailgas burner and then to the atmosphere. In order to reclaim the energy contained with the PSA exhaust gas, the exhaust gas could be fed to the boiler of a nearby facility where it would be consumed to create additional process heat for the facility. The heat from the PSA exhaust would also contribute to the boiler process heat. Alternatively, the heat from the PSA could be captured using a heat exchanger and fed to a nearby facility in the same manner as the waste heat collected by the heat exchanger on the fuel cell coolant loop. Nevertheless, the most effective use of the PSA waste heat and gases may be as input to the steam methane reformer. The scenarios in this study use the PSA waste in this manner.

Reformer Waste Heat

The steam-methane reformer (SMR) is a source of two types of waste heat. The stack exhaust, containing steam and other hot gases, provides a source of heat at a temperature exceeding 250°C. The SMR product gas is also at high temperature of nearly 700°C. Both of these heat streams can be captured through a heat exchanger. The SMR may also be designed to support heat inputs for upstream and downstream components steam production, fuel preheating, and the high/low temperature shift reactors.

Compressor Waste Heat

In the energy station process, hydrogen that will be stored in high-pressure containers either for vehicle fueling or fuel cell use in the future must first be compressed. During the compression process, the gas increases in temperature. A relatively small amount of heat can be captured during this process and used in a nearby facility.

2.2.5 Integration of Analyses with Vehicle Fleet Size and Fueling Needs

The station operational patterns will need to accommodate the hydrogen fueling needs of any fleet vehicles using the station. As hydrogen vehicle technology develops, it is expected that the hydrogen vehicle population at a given site will grow. As more vehicles use a given energy station, the operational pattern for that station will need to change to accommodate the additional refueling. Thus, the station may need to increase reformer load, reduce the amount of hydrogen consumed by the fuel cell and/or increase its hydrogen storage capacity.

Vehicle Fleet Size and Fueling

As daily hydrogen dispensing rate increases at a given energy station, a simple way to accommodate the increased hydrogen demand would be to reduce the daily fuel cell operation proportionally. As shown in Figure 2-7, such an operational strategy would allow a station to use most of its hydrogen to generate electricity in its early years, when few vehicles refuel daily, and eventually shift to servicing up to 12 vehicles a day.

This example assumes that each hydrogen vehicle pumps 5-kg of hydrogen per fill-up, and the reformer is operated continuously at full load. If full-load reformer operation isn't desired, then the number of vehicles per day will scale accordingly, as shown in Figure 2-8.

Figure 2-7. Number of Vehicles Served by a 50 kWhe Reformer Given Daily Fuel Cell Power Output

Figure 2-8. Number of Vehicles Capable of Daily 5 kg Fill-up under Given Reformer and Fuel Cell Operation

Figure 2-8 shows the number of hydrogen vehicles that can refuel on a given day for various average reformer loads and fuel cell power. This relationship would hold for a system that varies its reformer load and fuel cell load over time to match demand, as well as a system that is designed to operate at specific times during the day.

Evolution of Demand and Technology

Hydrogen vehicles are still several years from mass production. As a result, the number of hydrogen fueled vehicles is expected to increase gradually over time, as additional demonstration and small-volume production units are put in use. Energy stations offer an advantage over simple hydrogen fueling stations, in that any hydrogen not used by vehicles can be used to support building heat and power loads. As the hydrogen vehicle, fuel cell, and reformer technologies mature, it is expected that hydrogen vehicles will become more prevalent in the marketplace, eventually reaching beyond the fleet vehicle market.

As shown in the previous two figures, this increased demand can be accommodated without upgrading energy station equipment by using the fuel cell component of the energy station less, and increasing the reformer load. Only once the demand exceeds the reformer capacity would the system require additional equipment. However, if the timing of this upgrade is anticipated properly in the original design of the station, such an upgrade would not take place until after several years of station operation. Table 2-5 shows an example energy station capacity plan, with a near-, mid-, and long-term strategy. Given that only demonstration hydrogen vehicles have been put into use at the time of this report, it is likely that energy stations established in the near-term would be established in areas where they would be used by fleets, but not necessarily in areas where a large hydrogen fuel demand already exists.

Table 2-5. Example Near-, Mid-, and Long-term Operational and Service Capacity Scenarios for a Hydrogen Energy Station

	Daily Vehicle Hydrogen Fills	Max Fuel Cell Power (kWe)	Average Reformer Power (kWe)	Hydrogen Produced (kg/day)
Near-term	3	16	16.6	22.1
Mid-term	10	16	42.8	57.1
Long-term	30	40	126	168

The example energy station scenarios represented in Table 2-5 assume a fuel cell operation of 8 hours each day at the power level shown. Assuming that each vehicle fill requires 5 kg of hydrogen, the reformer system must provide the average power output shown in order to generate sufficient hydrogen for the fuel cell and the vehicles. In this example, the same reformer and fuel cell could be used for the near- and mid-term scenarios, potentially saving the cost of replacement for the long-term.

2.3 Selection of Most Promising System Options for Detailed Analysis

In order to determine which system configurations and operational patterns are most viable for an energy station, TIAX developed several criteria for selecting a representative set of technology configurations. TIAX applied these criteria to all possible technology configurations to determine an optimized set, as shown graphically in Figure 2-9. The optimized set best illustrates the range of viable energy station configurations and operational profiles.

Figure 2-9. Application of Filters to Determine Optimal Configurations for Analysis

As indicated in Figure 2-9, TIAX started with a list of possible alternatives for each major component of the system and generated a matrix of possible combinations of these components. In order to simplify the analysis of different system configurations (as the number of possible

combinations reached over 300), TIAX identified a baseline scenario comprised of the component options that are most commonly used in reformer systems, most readily available commercially, and/or simplest to implement. Six additional representative scenarios were selected that differ from the baseline scenario in terms of either cost, availability, simplicity, or scale (see Table 2-6). These representative scenarios, along with the baseline case, will be used to develop a representative cost and energy output estimate for the energy station in the second phase of this project.

2.4 Selection of Most Promising Operational Configurations for Detailed Analysis

As in Section 2.3, TIAX simplified the analysis of different operational configurations by identifying a baseline operational scenario and other representative scenarios. The scenarios encompass a range of power utilization strategies, vehicle refueling demand, and storage utilization (see Table 2-7). These representative scenarios, along with the baseline case, will be used to develop a representative cost and energy output estimate for the energy station in the second phase of this project.

Table 2-6. Representative Energy Station System Component Configurations

System Attributes	Major Components
Configuration I (high-pressure SMR)	Air Compressor (high pressure), SMR, PSA, Direct-Hydrogen Fuel Cell
Configuration II (low-pressure SMR)	Air Compressor (low pressure), SMR, PSA, Direct-Hydrogen Fuel Cell
Configuration III	Compressor, SMR, PrOx, Reformate Fuel Cell, PSA
Configuration IV	ATR, PrOx, Reformate Fuel Cell, PSA
Configuration V	Air Compressor, ATR, PSA, Direct-Hydrogen Fuel Cell

Table 2-7. Representative Energy Station System Component Configurations

System Attributes	Major Features
Baseline: Baseload operation	Constant reformer load, power load following fuel cell, medium-to-high storage
Load-following Operation	Load following reformer and fuel cell operation, low storage
Peak-power	Constant reformer load, peak hours fuel cell operation only, high storage
Timed Operation	Timed reformer and fuel cell operation, high storage

3. Assessment of Fleet Size and Locations (Task 2)

Energy station market potential is likely to be highest among users with a fleet of vehicles. These fleet users could be either commercial enterprises like businesses or utilities, or government fleets. Hydrogen vehicle fleet users may favor an energy station over a hydrogen fueling station because the CHP would offset some of the operational costs of their facility.

This section describes the potential for placing energy stations in locations with fleets. It reviews fleet characteristics in the U.S., incentives and/or regulations governing use of alternative fuel vehicles, the potential for optimal placement of energy stations among government fleets in the pilot phase, and facility characteristics that are well-suited for energy stations and fuel cell vehicles.

3.1 Potential for Energy Station Use by Fleets

Currently there are approximately 12 million fleet vehicles in the U.S. (Bobit 2001). This figure includes cars and trucks (Class 1-5) in fleets of 10 or more vehicles. Among cars and trucks, the most numerous operators of fleet vehicles are businesses. Among trucks, however, the combined government – at all levels – operates a rather large share of nearly 40%, as indicated in Table 3-1.

Table 3-1. Industry Distribution of Fleet Vehicles^a

Type of Fleet	Cars	Trucks (Class 1-5)
Rental ^b	26%	4%
Business	48%	49%
Government	14%	39%
Police	5%	<1%
Taxi ^c	2%	<1
Utility	5%	8%
<i>Total</i>	<i>6 million</i>	<i>6 million</i>

Source: Bobit Auto Group Research Department, 2001. (Additional information www.fleet-central.com)

^aFleets with more than 10 units

^bRental includes vans and SUVs in the car category, rather than truck

^cTaxi includes vans

Roughly 14,000 business and utility fleets with more than 25 vehicles operate over 4 million cars and trucks. However, the majority of fleets have between 5 and 24 vehicles. Among the small fleets, which number approximately 600,000, nearly 5 million cars and trucks and trucks exist.

3.1.1 Status of Government Fleets in the U.S.

The Federal government fleet vehicle population nationwide and in California is shown in Table 3-2.

Table 3-2. A Review of the Status of Government Fleet Vehicles
Indicates a Large Number of Vehicles in Operation

Fleet Type	Fleet Size
Federal Government Fleet Vehicles ^a	600,000 ^b
Federal Government Light Duty Fleet Vehicles in California ^c	40,000

^aFederal Motor Vehicle Fleet Reference Guide (July 2000)

^bVehicles purchased by the Office of Vehicle Acquisition and Leasing Services

^c2001 GSA Federal fleet vehicles

On a year by year basis, the GSA purchases 58,000 vehicles for Federal government fleets. If the portion of annual acquisitions in California is similar to California's fraction of Federal government vehicles in operation, this leads to a little less than 4,000 Federal vehicles acquired per year in California.

Alternative Fuel Vehicle Requirements

Among the vehicles acquired by GSA for government fleets are a small number of alternative fuel vehicles. These vehicles, which are powered by electric batteries or various forms of natural gas, propane, and flexible fuels (ethanol/gasoline), are purchased or leased due to federal or state regulations that require their use. Table 3-3 summarizes the regulations for alternative fuel use by fleets.

In addition to regulations that requires fleets to purchase low emission or alternative fuel vehicles, California and some northeastern states are developing low emission vehicle sales requirements for manufacturers. The California regulation on zero emission vehicles (ZEVs), which was referred to as the ZEV mandate, was settled in 2003 after a long period of dispute with the vehicle manufacturers. The most recent incarnation of the ZEV program will enable the manufacturers to comply with sales obligations through a combination of pure ZEVs, advanced technology partial ZEVs, and extremely clean conventional vehicles. Most relevant to the demand for energy stations, however, is the requirement to meet part of the ZEV obligation through sales of fuel cell vehicles. The total market requirement starts at 250 fuel cell vehicles by 2008 with an increase to 2,500 vehicles in 2009-2011, a further increase to 25,000 vehicles from 2012-2014, and 50,000 vehicles from 2015-2017. Fuel cell vehicles sold prior to 2008 count for credits in the ZEV program, which is expected to begin in 2005.

Aside from regulations, various incentives at the federal, state level, and local level, may provide some motivation for purchase of alternative fuels, including fuel cell vehicles. Table 3-4 summarizes some of the major incentive programs. Local incentives are fairly rare and usually target medium or heavy-duty vehicles.

Table 3-3. Alternative Fuel Fleet Regulations Influence Purchase and Leasing of Vehicles to Government Fleets, and to Some Extent Private Fleets

	Rule	Vehicles	Requirements	Effective
Federal	EPAct	Federal, State and Alt Fuel Providers	An increasing percentage of new light and medium duty vehicles must be alternative fuel. Credits could be collected for early compliance (until 1997) and for purchasing amount above required.	Starting 1992
South Coast Air Quality Management District	Rule 1191	Light- and medium-duty Public Fleet Vehicles	All public entities with fleets of 15 or more light-duty and/or medium-duty vehicles should procure only Low Emission Vehicles or cleaner vehicles.	Beginning July 1, 2001
	Rule 1192	Transit Bus Fleets	All public transit fleet operators with 15 or more transit vehicles or urban buses must acquire only alternative-fueled heavy-duty vehicles when adding or replacing buses.	Beginning (at the latest) July 1, 2001
	Rule 1194	Commercial Airport Ground Access Vehicles	All public and private fleets that provide passenger transportation services in the South Coast with 15 or more vehicles must acquire only ULEV, SULEV or ZEV vehicles. Percent of new purchase covered varies by vehicle type.	Beginning July 1, 2001

Table 3-4: Alternative Fuel Fleet Incentives Also Affect the Purchase and Leasing of Vehicles to Fleets

	Incentive	Vehicles	Benefit	Eligibility	Effective
Federal	Clean Fuel Vehicle Refueling Property Tax Incentive	Electric, Alternative Fuel, or Fuel Cell Vehicles	\$100,000 tax deduction for installation of clean fuel refueling	Any installation of a fueling facility	Through end of 2006
	Electric Vehicle (EV) Tax Incentive	Electric Vehicles	Tax credit for 10% of vehicle price up to \$4000	Full function EVs and city or neighborhood EVs. Note: Full function EVs are no longer available for purchase	Through end of 2006
	Tax deduction for hybrid electric vehicles (HEVs)	HEVs	\$2000 tax deduction for original owners of HEVs. Value decreases to \$500 by 2006 and is eliminated after 2006.	Vehicles certified by IRS; currently only Prius, Insight, Civic	Through 2006 with decreasing value
CA ARB	ZEV Incentive Program II (ZIP II)	Electric Fleet of at least two vehicles	Up to \$11,000 in grants for purchase or lease	Fleets in Environmental Justice Areas. Note, there are no longer any vehicles eligible for this program	Through June 30, 2004
	ZEV Fleet Incentive Program	Electric Vehicles	\$5,000 in grant	Any private or public business	Through June 30, 2004
South Coast Air District/Mobile Source Reduction Credit Program	Diesel Pollution Reduction Program	Medium and Heavy Duty Diesel Vehicles	Incremental costs toward purchase of new alternative fuel vehicles	Any private or public fleet operator	Individual proposals accepted through Jan, 2003

Source: <http://www.driveclean.ca.gov/en/gv/incentives>

The gap between available vehicles and adoption of them is apparent when reviewing the distribution of Federal vehicles by fuel type in California. Nearly all vehicles use conventional fuel, as indicated in Figure 3-1. Of those that are alternative fuel vehicles, most are CNG. Although the figure indicates an almost equal number of flexible fuel vehicles, the general experience in the U.S. is that use of ethanol in those vehicles is the exception rather than the rule.

Figure 3-1. Federal Fleet Vehicle Distribution by Fuel Type in California

3.2 Distribution of Government Facilities with Fleets

In looking for the ideal type of facility for an energy station, TIAX reviewed the types of facilities that currently have fleets. As Figure 3-2 indicates, the majority of fleets are operated by the Postal Service. Due to the size and complicated nature of jurisdiction and programming at the Postal Service, BKi's research suggested that this agency may be a good candidate to look at in the future but is not appropriate for preliminary study of energy station locations.

Veteran Administration facilities, although not large in number of fleets, initially stood out as a possibility because of their hot water requirements. Further research by BKi, however, found that the facilities do not generally have fleets large enough to require a vehicle program. Without a fleet manager running a program with some alternative fuel vehicle experience or interest, BKi felt that these facilities were not worth pursuing at this time.

The remaining facilities are mainly military or are under the jurisdiction of various federal agencies, including national laboratory facilities.

Figure 3-2. Federal Fleets are distributed Among Various Types of Facilities

3.3 Methodology for determining ideal energy station locations

In an effort to identify the ideal federal facilities for the near-term placement of hydrogen energy stations, TIAX and BKi created a list of ideal characteristics for the pilot project phase of development and commercialization. These characteristics, shown in Step 1 of Figure 3-3, formed the initial criteria by which the facility options were narrowed. Most, if not all, of the criteria needed to be met for an ideal energy station.

Initial contacts were made with local representatives of the General Services Administration (GSA) and the U.S. Department of Energy (DOE) to gain more information about potential sites. GSA is responsible for acquiring cars for most federal government agencies, which in turn lease the vehicles from GSA. GSA provided contact information for representatives from numerous agencies and BKi culled that list for agencies that have separate and distinct facilities in California. California was chosen as a good starting point for identifying the types of fleets and locations ideal for energy stations because the state government and regional air districts tend to create environments favorable to energy and air quality improvements. With potential sites available in California, TIAX could also control site visit costs due to its presence there. In addition to discussions with GSA representatives, GSA invited a BKi representative to make a presentation about this project to their Northern California AFV User Group. Feedback from this group provided further indications of the ideal characteristics for energy stations.

DOE provided contact information for the National Laboratory facilities in California along with updates about EPCa compliance.

A third source of contact information was the Clean Cities Coordinators. Clean Cities is a program sponsored by DOE that works to advance AFV use in public and private fleets. Each metropolitan area has at least one Clean Cities Coalition. The Coalition Coordinators were asked to provide contact information for members who represented federal facilities.

Figure 3-3. A Step-by-Step Process was Used to Determine the Characteristics of Facilities That Have High Potential for Use of an Energy Station

In addition to those contacts mentioned above, personnel at military facilities, Postal Service, the Veterans Administration, and the Departments of Defense and Interior (National Park Service) also were contacted.

For each federal agency contacted, BKi attempted to speak with both the fleet manager and the facility's energy manager. Fleet managers were asked about their existing vehicle fleet, experience with AFVs, and plans for future vehicle acquisitions. The study was particularly interested in facilities that currently operate compressed natural gas (CNG) vehicles since CNG is a gaseous fuel with many of the same properties and issues as hydrogen. In addition, each agency was asked how their vehicles were acquired. Lastly, BKi asked how the facility planned to meet future EPA requirements.

BKi stressed to each interviewee that the proposed hydrogen station would serve multiple purposes and that the facility's energy management practices and environment would be nearly as important as its fleet. Therefore, energy managers were asked about the facility's energy purchasing/generating plans, needs for backup power, and any details about future power needs. BKi also asked about the facility's use of natural gas and the locations of any distribution and transmission lines.

Following BKi's development of a list of agencies or facilities that possess the energy station criteria listed in Figure 3-3, TIAX further researched and/or visited the facilities to determine the characteristics that make them desirable. For example, since a desired criteria was to have use for hot water, TIAX visited a facility to determine what types of activities or utility systems exist

at the facility that cause it to require hot water. This type of analysis enabled TIAX to develop a design for the ideal facility to house and use an energy station.

3.4 Results of Site Research

Table 3-5 presents descriptions of the facilities deemed most appropriate for energy stations and fuel cell vehicles. They are ranked by level of interest stated by facility managers.

Table 3-5. Facilities Deemed Most Appropriate for Energy Stations and FCVs

Facility	Facility Description	Vehicle Description
A.	<ul style="list-style-type: none"> ▪ Military Facility ▪ Over 1000 structures on 2 square miles ▪ No on-site power generation 	<ul style="list-style-type: none"> ▪ Ongoing AFV program ▪ 4200 vehicles total ▪ 1200 AFVs ▪ Replace 350 vehicles/yr
B.	<ul style="list-style-type: none"> ▪ Military Facility ▪ Small facility – less than 400 acres ▪ No on-site generations ▪ Natural gas provided by local utility 	<ul style="list-style-type: none"> ▪ Eager to expand AFV program, especially fuel cell vehicles ▪ 70 Vehicles, 55 AFVs (mostly CNG) ▪ Replace 14 light duty trucks over next “few years”
C.	<ul style="list-style-type: none"> ▪ National Park with over 800 structures on 10 square miles ▪ Cogeneration facilities/hot water heating ▪ Major renovations occurring ▪ Purchases electricity at favorable rates 	<ul style="list-style-type: none"> ▪ 200 Vehicles ▪ 140 AFVs (mostly CNG but also EV) ▪ Served by two transit agencies ▪ Three natural gas shuttles in service
D.	<ul style="list-style-type: none"> ▪ Federal Laboratory ▪ Numerous structures on several hundred acres ▪ No on-site generation ▪ Purchases electricity at favorable rates 	<ul style="list-style-type: none"> ▪ Active AFV program and interested in hydrogen ▪ Potential collaboration with city and adjacent university ▪ 265 Vehicles: Some AFVs, most are EVs and FFVs ▪ Considering a natural gas refueling station
E.	<ul style="list-style-type: none"> ▪ Military Facility ▪ Large facility but isolated ▪ Some on-site generation, including cogeneration 	<ul style="list-style-type: none"> ▪ 235 Vehicles ▪ 40 AFVs, all CNG pick-up trucks ▪ Little potential for public access or collaboration
F.	<ul style="list-style-type: none"> ▪ Federal Laboratory ▪ Over 200 structures over several square miles ▪ No on-site generation ▪ Purchases electricity at favorable rates 	<ul style="list-style-type: none"> ▪ Ongoing AFV program, including construction of CNG refueling station ▪ 150 Vehicles: 20 AFVs, mostly CNG ▪ Leased through GSA ▪ Plan to replace most vehicles with CNG when refueling station is complete in 2003-2004
G.	<ul style="list-style-type: none"> ▪ Military Facility ▪ Several hundred structures on over 500 square miles ▪ Cogeneration facilities 	<ul style="list-style-type: none"> ▪ No AFV program currently but interested in future ▪ Several hundred light-duty vehicles
H.	<ul style="list-style-type: none"> ▪ Military Facility ▪ Interest in hydrogen for stationary applications ▪ On-site generation, including cogeneration 	<ul style="list-style-type: none"> ▪ Ongoing AFV Program ▪ Interest in hydrogen ▪ Potential collaboration with other nearby military facilities ▪ 600 Vehicles: 75 AFVs, all CNG ▪ Lease through GSA
I.	<ul style="list-style-type: none"> ▪ Federal Laboratory ▪ Over 100 structures on 200 acres ▪ Small cogeneration on-site 	<ul style="list-style-type: none"> ▪ Ongoing AFV Program ▪ 70 Vehicles: 9 AFVs, all CNG sedans/pickups ▪ Lease through GSA ▪ Will lease future vehicles from GSA as needed
J.	<ul style="list-style-type: none"> ▪ National Park ▪ Many different types of structures on small portion of 1500 square miles ▪ Small on-site generation plants 	<ul style="list-style-type: none"> ▪ Burgeoning AFV program ▪ Interested in augmenting AFV fleet, including fuel cell vehicles ▪ Several electric and propane vehicles

By comparing the characteristics of these facilities and further research with site visits, TIAX developed a list of ideals for an energy station location, as shown in Table 3-6.

Table 3-6. Characteristics of Facilities with High Potential for Energy Station Installations

Open-minded engineering / utility manager, Open-minded transportation manager		Vehicles return to terminal each day
Desire to have green image or participate in alternative energy projects.		Heavy-duty and light-duty vehicles
Buildings planned for renovations		Small set of fleet vehicle users
Variety of building types with: <ul style="list-style-type: none"> ▪ swimming pools ▪ hydronic heating ▪ laundry ▪ other hot water requirements

4. Evaluation of Building Integration (Task 3)

In order to take advantage of potential cogenerative heat uses and technologies, the likely amounts and grades of waste heat that will be produced from the reformer and stack(s) will need to be determined. Using the representative technology configurations above, TIAX performed an initial assessment of cogeneration opportunities. A more detailed analysis will be performed in Phase II of this project.

Design Approach

The preliminary design of the hydrogen energy station was developed as follows. First, a matrix of potential energy station systems was developed using hydrogen reformer type, fleet requirements, building thermal and electrical load requirements, and location as design variables. From this overall matrix, the most likely system candidates were selected for further analysis. The next step was to develop a sample system design with specifications. A hydrogen production and purification system using a steam reformer followed by a pressure-swing absorption purification system was selected for modeling using HYSIS™, a proprietary chemical process modeling software. The HYSIS™ model was used to establish the overall and stream-specific material-balance as well as design parameters of flow-rate, temperature and pressure. The process flow shown in Figure 4-1 is an example of a 55 kW fuel cell-based hydrogen energy station. This particular example shows the process flows for an energy station with a low-pressure reformer. The process flows for this energy station are discussed in detail in Section 4.3.

In conjunction with the process flow diagram, a process flow table was developed listing flow rate, pressure, and temperature for each element of the sample system (see Table 4-1). An important detail in the process flow diagram and table that is essential to the energy station concept is the description of the waste heat. There are five types of heat loss (shown as Q_1 - Q_5 in Figure 4-1) that can contribute to building heat loads. This is discussed further in Section 4.1 and 4.2.

The process flow diagram is a logical predecessor to the development of a piping and instrumentation diagram (P&ID) for the energy station. Figure 4-2 shows a P&ID that was developed for an example hydrogen energy station system.

4.1 Available Waste Heat

As discussed in Section 2.2.4, the energy station provides several sources of waste heat. Depending on which elements of the energy station are operating at any time, the waste heat sources could include the fuel cell, reformer, and hydrogen compressor.

Figure 4-1. Example Hydrogen Energy Station Process Flow Diagram

Table 4-1. Example of Hydrogen Energy Station Process Flow Table

Process Streams		Mass Flow, kg/hr								T	P	
		CH ₄	O ₂	N ₂	H ₂ O	H ₂	CO ₂	CO	OHC	Total	°C	Atm
1	Reformer feed natural gas	12.52		0.37			0.25		0.37	13.51	25	1.5
2	Reformer feed water/steam				35.14					35.14	25	1
3	Combustion air for reformer		17.93	59.01						76.93	25	1
4	Reformer product gas (hot)			0.37	18.72	3.95	13.20	11.55	0.85	48.65	684	1
5	Reformer product gas (cold) to PSA purifier			0.37	1.47	3.95	13.20	11.55	0.85	31.40	40	1
6	Reformer product gas (cold) pressurized to PSA purifier			0.37	1.47	3.95	13.20	11.55	0.85	31.40	40	10
7	PSA purifier product hydrogen to compressor				1.18	2.96				4.14	40	1
8	Compressed hydrogen to storage					2.96				2.96	30	245
9	PSA purifier product hydrogen to fuel cell					2.96				2.96	40	1
10	PSA residue gas as fuel to SMR combustor			0.37	0.29	0.99	13.20	11.55	0.85	27.26	40	1
11	SMR combustor exhaust gas (stack)			59.38	11.11	0.00	33.71	0.00	0.00	104.19	268	1
12	SMR combustor exhaust gas (cold)			59.38	4.57	0.00	33.71	0.00	0.00	97.65	64	1
13	SMR product gas knock-out water				17.25					17.25	40	1
14	Fuel cell input anode				0.15	2.96				3.11	40	1
15	Fuel cell input cathode		46.99	154.74	9.91					211.63	40	1
16	Fuel cell exhaust products		23.49	154.74	26.45	0.00	0.00	0.00	0.00	204.69	80	1
17	Fuel cell electricity											
18	SMR combustor exhaust knock-out water				6.54					6.54	40	1
Q ₁	SMR combustor stack heat										268	
Q ₂	SMR product gas heat										684	
Q ₃	3-stage hydrogen compressor heat rejection										40	
Q ₄	Fuel cell heat rejection loop										80	
Q ₅	Fuel cell exhaust product heat										80	

Assumptions:

Reformer steam/carbon ratio: 2.5

Ambient temperature: 25°C

Figure 4-2. Example Piping and Instrumentation Drawing for a Hydrogen Energy Station

Table 4-2 presents the heat rejection streams for an SMR-based energy station. A maximum of 73 kW can potentially be rejected — under the special case that both the storage compressor and the fuel cell are being operated simultaneously. In such a system, the SMR product gas heat of 24.6 kW, denoted as Q_2 is mostly utilized by the system to preheat the input feedstreams and effectively is not available for other purposes. Similarly, the 8-kW of heat rejected by the 3-stage compressor is not of useful quality. Therefore, the three main sources of heat usable for other applications such as building or process heating are: 7 kW from the SMR combustor stack, Q_1 ; 31 kW from the fuel cell coolant loop, Q_4 ; and 2 kW from the fuel cell exhaust gas, Q_5 . Thus, of the 73 kW heat rejected, typically 40-kW of heat is available, and that is when the fuel cell is operational.

Table 4-2. Available Heat from a Reforming and Fuel Cell System

Heat Source	Heat Description	Stream Type	Steam Temperature (°C)	Hot-Side Mass Flow (kg/hr)	Heat (kW)
Q_1	SMR combustor stack heat	gas	268	6.7	7.3
Q_2	SMR product gas heat	gas	684	17.8	24.6
Q_3	Compressor heat rejection	liquid	40	1.2	8.0
Q_4	Fuel cell heat rejection loop	liquid	80	26.5	31.1
Q_5	Fuel cell exhaust product heat	gas	80	178.2	2.1
Total					73

4.2 Evaluation of Potential Uses for Cogeneration Heat in Buildings

The heat demand for a typical building consists of space heating and hot water. The hot water, if used directly, is called domestic hot water (DHW). Examples of DHW applications are kitchens, laundry, showers, and swimming pools. Hot water may also be used for space heating. Depending on the temperature and flow rate of waste heat from an energy station, it may be able to contribute to these hot water or space heating demands.

Facilities near energy stations will need to select heating applications appropriate for the temperature of the waste heat. For example, a facility could make use of an energy station's lower temperature waste heat for hot water in swimming pools or showers and sinks. An energy station producing higher temperature waste heat also could support boiler or space heating loads. Figure 4-3 shows examples of configurations for various thermal applications.

Demonstration of fuel cell-based CHP applications by the U.S. Army Corps of Engineers have determined that there is potential to match the waste heat and thermal loads. Table 4-3 indicates example temperature demands for hospital and recreational facility thermal applications.

Figure 4-3. Potential Combined Cogeneration Applications of the Hydrogen Energy Station

Table 4-3. Examples of U.S. Military Hot Water Uses

Facility	Application	Application (Cold) Side Heating Loop	
		T _{in} (°C)	T _{out} (°C)
Swimming Pool	Pool Water	~27 ^a	~27 ^a
Recreational Facility	Showers	21	43
Recreational Facility	Absorption Chiller	83	97
Hospital	Space Heat	32 (summer)	43 (summer)
Hospital	Direct Hot Water	43	49

^aThe swimming pool is maintained at 27°C (80°F). Due to the large volume of water, the input and output temperatures vary only slightly from the temperature of the water.

Source: Several site reports from US Army Corps of Engineers. Engineer Research and Development Center. "Site Evaluation for Application of Fuel Cell Technology." 2001,

The swimming pool may be an appropriate use of waste heat from the energy station due to its moderate temperature requirements and low rate of heat loss. In a swimming pool application, the waste heat is used to maintain the pool temperature through a heat exchanger. Due to the fact that the pool water is not consumed, the small flow rate from the energy station can meet the load or is at least on the proper scale for partially meeting the load.

The Army Corps of Engineers' evaluation of the swimming pool at a military facility at Port Hueneme found that the waste heat from a 185 kW fuel cell (not including other forms of waste heat from energy station production) could provide the year-round heating requirements for its training pool. The heat from a 50 kW energy station could likely meet a major portion of the pool heating demands.

In addition to water and space heating options, the waste heat could also be used to support chemical processing, such as the conversion of waste kitchen grease to biodiesel. If a biodiesel production facility were co-located with an energy station, the station could be used to create the biodiesel in addition to hydrogen. Such an application assumes that the energy station is located near the chemical processing facility.

4.3 Analysis of Thermal, Hydrogen, and Electrical Resources Provided by an Energy Station

Buildings that would be well suited for an Energy Station would utilize both the thermal and electrical output of the station. Optimizing the generation and utilization of thermal energy, hydrogen, and electricity requires a detailed look at the energy transfer within the energy station and the transfer between the station and nearby facilities. TIAX selected the low pressure SMR configuration for an initial analysis of the energy and mass transfer expected from an operating energy station. The remaining configurations will be analyzed further in the next phase of this program.

The low-pressure SMR configuration includes a 55 kW fuel cell, low pressure SMR, compressor upstream of PSA, PSA, and a three-stage compressor for hydrogen storage. This configuration was previously shown in Figure 4-1.

As shown in Table 4-1, the input streams to the SMR are natural gas, water, and air. The outputs from the energy station are electricity, hydrogen, and waste heat. Table 4-4 summarizes the flow rates for natural gas and hydrogen, the two key materials flowing in the energy station. It is important to know these and all other flow rates in order to engineer a successful system but also in order to understand the resource requirements and operational costs.

The SMR-based energy station can have a number of operating scenarios. Four most likely scenarios are presented in Table 4-5. The greatest available heat, 40 kW, is for scenarios 1 and 3, when both the SMR and fuel cells are simultaneously operating. It can be argued that Scenario 1 will also lead to the highest energy efficiency for the specific energy station configuration discussed in this section.

Table 4-4. Major Inputs and Outputs of High Pressure SMR
55 kW Energy Station

Component	Process Flow Number	Input/Output	Mass Flow (kg/hr)
Natural Gas	1	Input	13.6
Hydrogen	7, 8, 9	Output	3.0

Table 4-5. Heat and Electricity Optimization for Energy Station Operation

Operating Scenario	Fuel Cell	SMR	Compressor	H ₂ to Storage	Fuel Cell Electricity (kW) ^a	Available Heat (kW)	
1. Fuel cell is receiving hydrogen from storage with simultaneous operation of SMR and high-pressure compression	On	On	On	Yes	55	Q ₁	7.3
						Q ₄	31.1
						Q ₅	2.1
						Total	40.4
2 Only storage of hydrogen occurring	Off	On	On	Yes	0	Q ₁	7.3
						Q ₄	0
						Q ₅	0
						Total	7.3
3 Fuel cell is receiving hydrogen directly from PSA while SMR is operational	On	On	Off	No	55	Q ₁	7.3
						Q ₄	31.1
						Q ₅	2.1
						Total	40.4
4 Fuel cell is receiving hydrogen from storage. Reformer not operating	On	Off	Off	No	55	Q ₁	0
						Q ₄	31.1
						Q ₅	2.1
						Total	33.2

^aFrom fuel cell

5. Recommended Areas of Further Study

The first phase of this study considered the benefits of establishing a hydrogen-producing energy station, how to locate a potential host, and basic system and operational configurations of an energy station. Further investigation is needed to assess the specific design requirements, comparative costs, emissions, and operation of these representative configurations. Using the representative energy station configurations outlined in this phase, the utilization costs and related output should be determined for target host sites. Additionally, the potential participants in developing such a system and the related hydrogen infrastructure should be contacted in order to ascertain their interest. Finally, an analysis is needed of the different types of barriers and obstacles facing hydrogen infrastructure development, and of the extent to which the federal government will need to support these efforts.

6. Conclusion

This project has identified a set of representative technologies and representative operational scenarios that are being analyzed to estimate the size, power output, and cost of a hydrogen energy station. Ultimately, the goal of this project is to identify a Federal facility that could host a hydrogen-producing energy station and make use of residual heat through cogeneration, electrical output from a fuel cell, and provide fueling for on-site or nearby hydrogen vehicles. Several options have been identified for system configuration and operation, with each focusing on a different benefit: conventional system components, lower cost, small-scale operation, and design simplicity. Several Federal facilities have been identified as potential host sites, meeting most of the energy station host criteria developed as a part of this project. Energy and cost estimates will be presented in the final report of this project.

1. Bevilacqua, Knight, Inc., "Bringing Fuel Cell Vehicles to Market: Scenarios and Challenges with Fuel Alternatives," Prepared for California Fuel Cell Partnership, October 2001.
2. Thijssen, J., et al., "Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles," Phase II Final Report to DOE, Prepared by Arthur D. Little, Inc (TIAX), February 2002.

Technical Analysis of the Hydrogen Energy Station Concept

Phase II Report

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Report to the
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1. Introduction

The purpose of this technical analysis was to analyze the development of a hydrogen-dispensing infrastructure for transportation applications through the installation of a 50-75 kW stationary fuel cell-based energy station at federal building sites. The various scenarios, costs, designs and impacts of such a station were quantified for a hypothetical cost-shared program that utilizes a natural gas reformer to provide hydrogen fuel for both the stack(s) and a limited number of fuel cell powered vehicles, with the possibility of using cogeneration to support the building heat load.

1.1 Summary from Phase I

Phase I of this analysis involved the preliminary determination of potential host sites for an energy station. The Phase I analysis also involved the determination of representative system configurations, representative operational strategies, and representative building integration strategies. To carry out the Phase I analysis project as effectively as possible, TIAX structured a program that consisted of three major tasks.

1.1.1 Phase I Approach

Task 1 — Analyze System Cost and Performance. The first task conducted in this project was to evaluate all of the competing technologies that could be utilized for each of the components in the entire fuel cell and vehicle fueling system, based on the criteria of cost, performance, and technical feasibility. The goal of this initial, broad based assessment was to select the most promising (four to five) system designs and technologies on the basis of the above criteria.

Task 2 — Assess Public/Private Fleet Size/Locations. Data on the potential for energy stations with fleets were collected from a representative and diverse composition of stakeholders. Other key sources of information for projecting hydrogen vehicle fleet size and location included the EPA fleet administrators, who helped us determine their current and projected AFV fleet practices. Finally, other policies, such as the California Zero-Emission Vehicle (ZEV) Mandate and the ARB transit fleet regulation, that will either directly or indirectly encourage hydrogen fleets, were analyzed for their potential impacts.

Task 3 — Evaluate Building Integration. Using the results of Task 1 and a limited number of system designs and technologies selected for further analysis, the likely amounts and grades of waste heat that will be produced from the reformer and stack(s) was determined for a representative system configuration. With this information, cogenerative heat uses and technologies were researched and evaluated with respect to beneficial utilization in a commercial/ government building setting, as well as the cost and technical feasibility of those applications.

1.1.2 Phase I Results

Analysis of System Performance (Task 1)

A hydrogen-producing energy station reforms a hydrocarbon fuel, such as natural gas, to produce hydrogen for fuel cell operation and for dispensing to hydrogen-powered vehicles. The electrical power generated by the fuel cell and/or the residual heat from the system processes may be used to support energy station and nearby building power and heat loads. The fraction of reformer output ultimately used by hydrogen vehicles is first purified and stored for dispensing upon demand.

In order to determine which system configurations and operational patterns are most viable for an energy station, TIAX developed several criteria for selecting a representative set of technology configurations. TIAX applied these criteria to all possible technology configurations and determined a representative set. This set represented the range of viable energy station configurations and operational profiles, providing the basis for developing representative cost and energy output estimates for the energy station in Phase II of the study.

The possible operational scenarios described in Phase I included peak power shaving, constant baseload operation, scheduled operation, on demand operation, and/or load following. These options are not necessarily exclusive – in some cases they may be used in combination. For example, one possible operational mode would be to hold the reformer load constant, while the fuel cell load follows the combined station and building loads.

Assessment of Public and Private Fleet Size and Locations (Task 2)

In its effort to identify candidate federal facilities for the placement of a hydrogen fueling station, TIAX worked with its subcontractor, Bevilacqua-Knight, Inc. (BKI), to create a list of characteristics that the ideal location should possess. These characteristics formed the criteria by which the facilities would be judged.

For each federal agency contacted, BKI attempted to speak with both the fleet manager and the facility's energy manager. Fleet managers were asked about their existing vehicle fleet, experience with AFVs and plans for future acquisitions. TIAX was particularly interested in facilities that currently operate compressed natural gas (CNG) vehicles since CNG is a gaseous fuel with many of the same properties as hydrogen. In addition, each agency was asked about how their vehicles were acquired. Lastly, TIAX asked how the facility planned to meet future EPA requirements.

Evaluation of Building Integration (Task 3)

In order to take advantage of potential cogenerative heat uses and technologies, the likely amounts and grades of waste heat available from the reformer and stack(s) needs to be determined for each of the representative system configurations determined in Task 1. In Task 3, the amounts and grades of waste heat available in one of the representative configurations was determined. This approach was later duplicated under Phase II for the remaining representative configurations.

1.2 Analysis for Advancement of Hydrogen Technologies (Phase II)

Using the specific energy station configurations outlined in Phase I, the utilization costs and related output were determined for target host sites. Additionally, the potential participants in developing such a system and the related infrastructure were contacted in order to ascertain their interest. To complete this analysis project as effectively as possible, TIAX structured Phase II to consist of four tasks, including one reporting task. The following subsections describe the project scope and methodology for the second phase of the project.

1.2.1 Scope of Work

Table 1-1 shows the Work Breakdown Schedule (WBS) for the Phase II activities.

Table 1-1. Work Breakdown Schedule for Phase II

Task 5 — Analyze Integrated power and fueling system
5.1 Determine integrated system costs
5.2 Estimate emissions
5.3 Assess integration of cogeneration and electric power heat
5.4 Evaluate fueling capacity issues
Task 6 — Explore Private and Public Partnerships
6.1 Contact potential private partners
6.2 Ascertain activities of current private and public partnerships
6.3 Evaluate role of policy/tax provisions
Task 7 — Identify Barriers to Hydrogen Use
7.1 Assess key technological hurdles
7.2 Evaluate cost obstacles
7.3 Determine needed policy changes
7.4 Determine public perception obstacles
7.5 Identify additional R&D
7.6 Assess total infrastructure cost and Federal cost share needs
Task 8 — Final Report
8.1 Interim reports summarizing year two milestones
8.2 Project final report
8.3 Presentation for annual peer review meeting

Task 5—Analyze Integrated Power and Fueling

Task 5 provided a more detailed analysis and modeling of the technologies and system designs that were selected in Task 1. This analysis evaluated and quantified the following for each of the selected systems and technologies: costs; emissions; cogeneration heat output, use, and potential applications; fuel cell stack electricity output; number of vehicles to be fueled; optimum vehicle fueling time; and hydrogen storage options.

Task 6—Explore Private and Public Partnerships

In order to explore and evaluate the opportunities for the use of public-private partnerships in hydrogen-fueling infrastructure development, TIAX contacted various types of potential private and public partners to determine their interest and/or plans to engage in such ventures. These partners included automakers oil/energy companies, utilities, commercial hydrogen producers, hydrogen technology developers, public transit agencies, federal, state and local government agencies, non-governmental organizations (NGOs), environmental advocacy organizations, and others. As part of this investigative process, we determined existing and planned public-private partnerships and undertakings related to the development of a hydrogen fuel infrastructure, and evaluated their success.

Task 7—Identify Barriers to Hydrogen Use

In Task 7, TIAX made an assessment and analysis of the different types of barriers and obstacles facing the development of a hydrogen infrastructure, including: key technological hurdles, cost obstacles, policy barriers and needed changes, and public perception issues.

TIAX also determined areas requiring additional research and development and formed recommendations. Finally, an analysis was made of the projected costs for developing a hydrogen fueling infrastructure.

Task 8—Final Report

This Phase II report summarizes the results of tasks that were completed in the second year of this project. The final report will incorporate the entire two-year project. In addition to delivering the final report, the results of the project will be presented at a peer review meeting.

1.2.2 Methodology

Detailed System Analysis

The system analysis assessed the operational scenarios and costs of establishing a hydrogen energy station. The representative energy station operational scenarios were designated to encompass the range of characteristics possible with an energy station. We then projected electricity and fuel costs, building heat and power loads, and hydrogen vehicle usage in the near- and long-term. The cost estimate was based upon various vendors' input, U.S. Department of Energy (DOE) targets, and TIAX projections of future technology and fuel prices. Net emissions from an energy station were determined by projecting emissions from energy station equipment and life cycle emissions from the fuel consumed by the station and compared to the baseline emissions generated by a standard boiler system and a reformer-based hydrogen fueling station. The net emissions were the difference between the baseline configuration and the expected emissions from an energy station providing combined heat and power supply to nearby building or buildings.

Identification of Public and Private Partnerships

In order to bring an energy station from concept to construction and operation, many types of partners are required. A close working group of partners is even more important during the near-term adoption of the technology.

TIAX recommends finding partners that can participate in multiple aspects of the project development. The appropriate partners for different project phases in the near-term are shown in Figure 1-1. They are design, construction, and operation phases. In the near term, the partners will likely include public and private funding sources and organizations conducting demonstration programs. Over time, the partners will become mainly private sector investors and commercial ventures.

Component and Station Design	Station Construction	Station Operation	
<ul style="list-style-type: none">♦ Project management / system integration: TIAX♦ Energy company♦ Gas/electric utility♦ Manufacturers (fuel cell, reformer, purification)♦ Demonstration site	<ul style="list-style-type: none">♦ Project management: TIAX♦ Energy Company♦ Gas/electric utility♦ Manufacturers♦ Public funding agency♦ Demonstration site	Station: <ul style="list-style-type: none">♦ Energy company♦ Gas utility♦ Electric utility	Vehicles: <ul style="list-style-type: none">♦ Transit vehicles♦ Federal fuel cell demo program♦ State fuel cell demo program♦ H2 ICE programs♦ Others

Figure 1-1. Partners for Three Phases of an Energy Station Project in Today's Market

For this project, TIAX identified partners who could benefit from an on-site energy station through screening federal facilities and federal agencies with alternative fuel vehicle programs. The screening process occurred as part of Phase I of the energy station project. Lists of facilities to screen were obtained through TIAX attendance at conferences and meetings, and discussions with personnel at federal agencies. Potential partners were interviewed to determine how their sites matched a list of criteria that TIAX had developed. These criteria are explained in the Phase I report. In addition, non-federal facilities with the appropriate co-generation and fueling demands were approached to gauge their interests in becoming project partners.

In addition to identifying a partner that will host an on-site energy station, it is necessary in the near-term to identify vendors who could participate in the design and installation phases of the project. TIAX identified a manufacturer/vendor through existing contacts with participants in the industry.

Due to the increasing interest in hydrogen infrastructure, TIAX found that energy companies might be very interested in becoming partners in early hydrogen infrastructure and fuel cell projects, such as a near-term energy station. Energy companies that historically were only

involved in the oil and gas business are now increasingly becoming involved in hydrogen and renewable energy technologies. An energy company can help in the design of a successful fueling station and may also be interested in operating the station. TIAX's presentations to members of this industry have resulted in considerable interest.

Another set of important participants are the gas and electric utilities. Although the fuel cell and hydrogen fueling elements of the energy station concept are not new to the utilities, the integrated concept may still be novel enough to need input from gas and electric utilities. The project would benefit from utility participation due to issues of grid connection, changes to electricity services, and negotiated rates. The utilities benefit from participation by being better able to provide services to customers later who build similar systems. TIAX has identified utilities based on available services at potential sites.

2. Analysis of Integrated Power and Fueling (Task 5)

As discussed in the Phase I report, several equipment configurations and operational scenarios are possible for an energy station. In Phase I of this study, we selected a set of representative station configurations and operational scenarios, in order to facilitate a detailed analysis of the power, heat, and fueling capabilities of future energy stations. These representative sets are shown again in Table 2-1.

Table 2-1. Representative Energy Station System Component Configurations and Operational Scenarios

System Configurations	Major Components
Configuration 1 (high-pressure SMR)	Air Compressor (high pressure), SMR, PSA, Direct-Hydrogen Fuel Cell
Configuration 2 (low-pressure SMR)	Air Compressor (low pressure), SMR, PSA, Direct-Hydrogen Fuel Cell
Configuration 3 (low-pressure SMR)	Compressor, SMR, PrOx, Reformate Fuel Cell, PSA
Configuration 4	ATR, PrOx, Reformate Fuel Cell, PSA
Configuration 5	Air Compressor, ATR, PSA, Direct-Hydrogen Fuel Cell
Operational Scenarios	Major Features
1: Baseline: Baseload operation	Constant reformer load, power load following fuel cell, low-to-medium storage
2: Load-following Operation	Load following reformer and fuel cell operation, low storage
3: Peak-power	Constant reformer load, peak hours fuel cell operation only, high storage
4: Back-up Power	On-demand fuel cell and reformer operation, high storage

Under Phase II of this study, we performed a detailed analysis of these representative system configurations and operational scenarios to determine their related energy demand and production, hydrogen production and storage needs, pollutant emissions, and system costs. Section 2.1 discusses details of the various representative operational scenarios, identifying the hydrogen throughput and storage requirements for each. Section 2.2 describes how the representative system configurations were used as inputs to a detailed energy flow analysis, and presents an estimate of the useful heat and electrical output for each representative system. Section 2.3 describes the difference between net energy station emissions and net hydrogen station emissions for each of the representative system and operational configurations. Section 2.4 describes the results of the cost comparison between establishing an energy station in place of a hydrogen fueling station.

2.1 Energy Station Operational Scenarios

In order to evaluate the specific attributes of the operational scenarios shown in Table 2-1, we developed a specific time-of-day operational profile for each scenario. These time-of-day profiles are presented in Figures 2-1 through 2-4, along with a description of the related power production, fueling throughput, and hydrogen storage requirements. Although an in-use energy station could serve a wide variety of building loads and refueling profiles beyond those shown below, the profiles in Figures 2-1 through 2-4 were selected as representative of the many profiles possible. The sensitivity of throughput and storage requirements to variations in these profiles was explored and is discussed below.

At an energy station, the system hydrogen storage capacity is not only dependent upon the vehicle fueling throughput and fuel cell hydrogen demand, but also the times when the reformer, fuel cell, and vehicle refueling systems operate. In order to understand the tradeoff between how much hydrogen is consumed by vehicle refueling and how much hydrogen is available for fuel cell consumption, the hydrogen consumption for each of these pathways was tabulated for each of the profiles in Figures 2-1 through 2-4. As shown in the tables at the bottom of these figures, if the hydrogen production capacity for the station does not increase with increased hydrogen fueling throughput, the fuel cell will need to operate at lower levels in order to leave sufficient hydrogen for vehicle refueling.

In the tables on the bottom of Figures 2-1 through 2-4, the maximum average daily fuel cell output is shown for a given daily vehicle throughput, assuming that the energy station electricity requirements are met separately. If the energy station is designed to operate only with electricity from the fuel cell, then the maximum number of vehicles that can refuel per day will be lower, because more hydrogen will be needed by the fuel cell to operate whenever the reformer or refueling systems are in use.

As shown in the tables on the lower right of Figures 2-1 through 2-4, increased hydrogen production capacity (i.e., increased reformer size) will affect the storage requirements differently depending upon which operational scenario is in use. Table 2-2 summarizes how increasing reformer size from 50 kWe to 100 kWe qualitatively affects storage capacity (see Figures 2-1 through 2-4 for specific values).¹

In these profiles, heat utilization was not constrained to a certain target value, but was allowed to vary based on target electricity and hydrogen production. It was assumed that an actual energy station would be designed to meet specific electrical and hydrogen production targets, and the heat recovery component would be designed to capture whatever useful heat was available. This assumption seemed appropriate given that energy stations would never be operated solely to generate heat; hydrogen and/or electricity would always be produced as well.

¹ In this study, a reformer rated at 100 kWe capacity corresponds to a reformer adequately sized to supply, at full load, enough hydrogen to operate a fuel cell producing 100kWe AC power.

In the base-loaded operational profile shown above, a 50 kWe capacity reformer is supporting a 32 kWe fuel cell load and 18 kWe equivalent of hydrogen demand from the 3 refueling vehicles during overnight slow-filling of hydrogen vehicles. When the vehicles are not refueling, the fuel cell and reformer are operated at 50 kWe output. Under these operating conditions, hydrogen production always balances the hydrogen consumption; thus, little buffer storage is required.

If the number of refueling vehicles were to increase, or the off-peak building demand drops below 32 kWe, the fuel cell output could be lowered. The 50kWe capacity reformer can produce enough hydrogen to fuel up to 13 light-duty vehicles per day, assuming 5 kg per fill. However, this would leave very little hydrogen for fuel cell consumption (see table below).

Number of Cars per Day (5kg/fill)	3	5	7	10	13
Average Reformer Output (kWe equivalent H ₂)	50	50	50	50	50
Average Fuel Cell Output during fueling (kWe)*	32	20	8	0	0
Average Fuel Cell Output when not fueling (kWe)*	50	50	50	33	3.3
Storage Required (kg, 3x minimum requirement)	0	0	0	25	70

*Represents maximum power available to nearby facilities (parasitic losses met separately)

ATTRIBUTES:

- Minimal storage option
- Always-on fuel cell and reformer — avoids low-production warm-up phases
- Slow-fill overnight refueling — avoids the need for a larger compressor used in standard, or fast-fill, refueling

STORAGE OPTIONS:

- OPTION 1: Operate the reformer at a constant output that will meet the fuel cell and vehicle refueling demand at all times (see chart), letting the fuel cell load increase when no vehicles are refueling. This would require only enough storage to buffer against fuel cell and refueling demand changes that outpace reformer output adjustments (see table below).
- OPTION 2: Could also size reformer to generate enough hydrogen under constant operation to support the cumulative daily fuel cell and vehicle refueling hydrogen demand, without necessarily meeting hydrogen demand at all times. This would require sufficient storage for excess hydrogen during periods of low demand.

Max. Reformer Output (kWe equiv. H ₂)	75	100
Maximum number of 5 kg fills/day	20	26
Avg. F.C. Output during fueling (kWe)*	30	50
Avg. F.C. Output when not fueling (kWe)*	50	50
Storage Required (kg)*	38	56

*Assuming 10 vehicle fills/day, 5 kg each

Figure 2-1. Scenario 1: Base-loaded Energy Station Operation

ATTRIBUTES:

- Matches station operation to time-of-day hydrogen demand from fuel cell and vehicle refueling
- Always-on fuel cell and reformer — avoids low-production warm-up phases
- Fast-fill refueling of vehicles in the morning and evening shown in diagram

STORAGE OPTION:

- Operate the reformer as load-following, generating excess hydrogen at a low rate until the storage is replenished. When the demand outpaces hydrogen production, hydrogen is taken from storage to make up the difference. Reformer will operate at full capacity until a predetermined threshold is met, at which point the replenishment rate will return to the off-peak rate.

In the load-following operational profile shown above, a 50 kWe fuel cell follows the building demand, providing maximum power during peak hours and operating at a reduced load during off-peak hours. In turn, the 50 kWe reformer follows the load demand from the fuel cell and vehicle refueling systems. In cases where the demand from the fuel cell and vehicle fueling outstrips the hydrogen produced by the reformer, hydrogen will be taken from storage to make up the difference. Once the demand drops below the reformer capacity limit, the reformer continues to operate at maximum load until the storage is sufficiently replenished.

Number of Cars per Day (5kg/fill)	3	5	7	10	13
Average Reformer Output (kWe equivalent H ₂)	47	50	50	50	50
Average Fuel Cell Output during fueling (kWe)*	36	33	25	13	1.6
Average Fuel Cell Output when not fueling (kWe)*	36	31	23	12	1.1
Storage Required (kg, 3x minimum requirement)	33	61	64	73	92

*Represents maximum power available to nearby facilities (parasitic losses met separately)

Max. Reformer Output (kWe equiv. H ₂)	75	100
Maximum number of 5 kg fills/day	20	26
Avg. F.C. Output during fueling (kWe)*	36	39
Avg. F.C. Output when not fueling (kWe)*	36	40
Storage Required (kg)*	84	67

*Assuming 10 vehicle fills/day, 5 kg each

Figure 2-2. Scenario 2: Load Following Energy Station Operation

In the peak-shaving operational profile shown above, a reformer is supporting a 50 kWe fuel cell load during peak load hours and any hydrogen demand from the refueling vehicles. In cases where the demand from the fuel cell and vehicle fueling outpace hydrogen production, hydrogen will be taken from storage to make up the difference. When the demand drops to below the maximum reformer production load, the reformer continues to operate at maximum load until the storage is sufficiently replenished.

In order to accommodate larger hydrogen demands while avoiding variations in reformer operation the reformer could also be operated continuously at a set load and/or the fuel cell output could be lowered. The 50kWe reformer can produce enough hydrogen to fuel 13 light-duty vehicles per day, assuming 5 kg per fill, leaving little hydrogen for fuel cell consumption.

Number of Cars per Day (5kg/fill)	3	5	7	10	13
Average Reformer Output (kWe equivalent H ₂)	28	35	43	50	50
Average Fuel Cell Output during fueling (kWe)*	0	0	0	0	0
Average Fuel Cell Output when not fueling (kWe)*	21	21	21	16	1.6
Storage Required (kg, 3x minimum requirement)	9	33	63	92	92

*Represents maximum power available to nearby facilities (parasitic losses met separately)

Max. Reformer Output (kWe equiv. H ₂)	75	100
Maximum number of 5 kg fills/day	20	26
Avg. F.C. Output during fueling (kWe)*	0	0
Avg. F.C. Output when not fueling (kWe)*	21	21
Storage Required (kg)*	54	38

*Assuming 10 vehicle fills/day, 5 kg each

ATTRIBUTES:

- Peak-shaving fuel cell operation (i.e., operates only during peak-load hours)
- Reformer operates only during refueling, during peak hours, or after peak hours until hydrogen storage is filled
- Fast-fill refueling of vehicles in the morning and evening shown in diagram

STORAGE OPTIONS:

- OPTION 1: Operate the reformer at levels that will meet the fuel cell and vehicle refueling demand at all times (see chart), continuing to operate until storage is sufficiently replenished. Sufficient storage is needed to provide hydrogen in cases where the vehicle refueling load exceeds the reformer output (see tables below).
- OPTION 2: Could also size reformer to generate enough hydrogen under constant operation to support the cumulative daily fuel cell and vehicle hydrogen demand, without necessarily matching hydrogen demand at all times. This would require sufficient storage for excess hydrogen generation during off-peak hours and excess demand during peak hours.

Figure 2-3. Scenario 3: Peak-shaving Energy Station Operation

ATTRIBUTES:

- Fuel cell operates only as back-up power
- Reformer operates to support vehicle refueling and back-up power as needed
- Fast-fill refueling of vehicles in the morning and evening shown in diagram

STORAGE OPTION:

- Operate the reformer to match the hydrogen demand from fuel cell and vehicle fueling. When the demand is larger than the reformer production rate, additional hydrogen will be taken from storage to make up the difference. After the hydrogen demand drops, the reformer will operate at full load until the hydrogen supply is replenished.

In the back-up power operational profile shown above, the 50 kWe fuel cell is activated when back-up power is needed. The fuel cell is operated to match the building load up to its 50 kWe capacity. If insufficient hydrogen is available, the fuel cell system operates at a lower load until sufficient hydrogen can be produced. The 50 kWe reformer supports the vehicle refueling and fuel cell loads.

Although ample reformer capacity is available for the 3 to 7 vehicles/day scenarios shown in the table below, a larger number of vehicles would prevent the fuel cell from operating at full power for all of the back-up periods as shown due to a lack of sufficient hydrogen. In such cases, the fuel cell would have to operate at a reduced load, or additional reformer capacity would need to be added in order to accommodate such a back-up power demand (see tables below).

Number of Cars per Day (5kg/fill)	3	5	7	10	13
Average Reformer Output (kWe equivalent H ₂)	30	38	45	50	50
Average Fuel Cell Output during fueling (kWe)*	30	30	30	20	2.0
Average Fuel Cell Output when not fueling (kWe)*	16	16	16	11	1.1
Storage Required (kg, 3x minimum requirement)	20	33	50	69	89

*Represents maximum power available to nearby facilities (parasitic losses met separately)

Max. Reformer Output (kWe equiv. H ₂)	75	100
Maximum number of 5 kg fills/day	20	26
Avg. F.C. Output during fueling (kWe)*	30	30
Avg. F.C. Output when not fueling (kWe)*	16	16
Storage Required (kg)*	58	48

*Assuming 10 vehicle fills/day, 5 kg each

Figure 2-4. Scenario 4: Back-up Power Station Operation

Table 2-2. Effect of Increasing Reformer Size

Operational Scenario	Change in Storage Requirement ^a	Change in Fuel Cell Output*	Time of day of Change in Fuel Cell Operation
1	Increases	Increases	All day
2	Increases for 75 kWe, decreases for 100 kWe	Increases	All day
3	Decreases	Increases back to low vehicle throughput levels	Midday
4	Decreases	Increases to low vehicle throughput levels	Afternoon, evening

^aRelative to 10 vehicles/day, 50 kWe system; assumes reformer operation would follow load profile similar to the 50 kWe system

The preference for which operation scenario is used will depend upon a particular site's need for power and heat on the average and throughout the day, the importance of the emissions reductions (e.g., facility emission requirements or emission trading opportunities), and the net cost of operation. The key attributes of the operating scenarios are described below.

2.1.1 Hydrogen Storage and Energy Usage

An energy station system must provide sufficient hydrogen storage to meet the constraints of vehicle fueling and fuel cell power demand combined with turn-down capabilities of the reformer. Continuous reformer output requires the hydrogen product to be consumed by the fuel cell, compressed and stored, or compressed and filled into the vehicle.

Overnight vehicle filling as illustrated in operating Scenario 1, mitigates the storage requirement whereas intermittent fueling demands illustrated in Scenarios 2, 3 and 4 increase the overall storage requirement.

Adjusting reformer output and fuel cell demand can also reduce the overall storage requirement. Scenarios 3 and 4 illustrate the effect of shutting down the reformer when the demand for hydrogen is low. Complete shut down of the reformer is illustrated in Scenarios 3 and 4. This degree of reformer turn down may not be practical because of heat losses and potential accelerated degradation of the catalyst.

2.2 Energy Production and Usage Modes

2.2.1 General Description of Energy Station Configurations and Design Bases

Five representative hydrogen energy station systems/configurations were considered as noted in Table 2-1. The following descriptions of each configuration present a summary of key parameters and processes for each of the five configurations.

Three of the five configurations use a steam methane reformer (SMR) as the source of hydrogen/fuel for driving the fuel cell. In general, the SMR system under consideration consists of a catalytic natural gas reformer, a high temperature shift (HTS) reactor, and a low temperature shift (LTS) reactor. The reformer products are purified to produce pure hydrogen using a pressure swing adsorber (PSA). The residual stream from the PSA is rich in carbon monoxide (CO) and hydrogen and is returned to the combustion chamber of the reformer to provide heat for the endothermic reformation reactions. The purified hydrogen is stored as a high-pressure gas (425 atm) for vehicle refueling. In Configurations 1 and 2, the purified hydrogen is feed directly to the fuel cell.

In Configuration 3, the fuel cell is fed the product reformat stream directly from the SMR reactor system. To avoid fuel cell catalyst poisoning, a preferential oxidation (PrOx) reaction step is added after the LTS section in the SMR reactor system. Traces quantities of CO leaving the LTS are reduced in the PrOx reactor. A PSA system is also present to store purified hydrogen for vehicle refueling.

Configurations 4 and 5 use an autothermal reformer (ATR) system for the production of hydrogen/reformat for driving the fuel cell. The ATR system considered here consists of a reformer section, an HTS section, an LTS section, and a PrOx section. Fuel, air, and steam react in the reformer section to form primarily a mixture of nitrogen, hydrogen, CO, and carbon dioxide (CO₂). CO reacts with steam in the HTS and LTS, and final traces of CO are reduced in the PrOx reactor. In Configuration 4, the fuel cell is directly fired by the ATR reformat product. A key difference in the system configuration between the SMR and the ATR systems is the use of the PSA residue stream, or the fuel cell exhaust stream in Configuration 3, to fire the SMR combustor. In the ATR system, the net reactions are sufficiently exothermic that the residual stream from the fuel cell, or the PSA, is available as cogeneration heat.

Waste heat is available for capture at various points in the system. These capture points include heat rejected by the SMR/ATR product gas as it is cooled for purification or as input to the fuel cell, heat rejected by the fuel cell cooling loop during fuel cell operation, the heat rejected by the fuel cell exhaust stream, and the heat rejected by the multi-stage high pressure compression system. Typically the former three sources of waste heat have the greatest potential for cogeneration heating and will be discussed in detail later in this section. The following describes the design criteria for the five configurations.

2.2.2 Design Criteria

At the core of the design for each of the five energy station configurations was the selection of a common 55-kWe DC output hydrogen fuel cell. The hydrogen production systems were designed to continuously provide fuel to the 55-kWe fuel cell. Therefore, the size of the reformer system was determined by the hydrogen requirements of the fuel cell. Also common to the five systems was the use of natural gas as the basic fuel for producing hydrogen.

As noted previously, Configurations 1, 2, and 3 were SMR-based systems and Configurations 4 and 5 were ATR-based systems. The key components in each of the five systems are described below along with the design assumptions. A detailed process flow chart delineating the various process streams for each configuration is presented in Appendix A.

Configuration 1: SMR at High Pressure with Hydrogen Fuel Cell

In this configuration, the SMR is operated at a nominal pressure of 10 atm. Most developers have built simpler atmospheric reformers for small scale applications, so the high pressure design represents a more advanced configuration. As noted previously, the SMR reactor system consists of a reformer reactor, an HTS reactor and an LTS reactor. Product from the SMR is cooled and fed to the PSA purification system. Following the PSA, the hydrogen is either fed to the fuel cell directly (after some reduction in pressure), or it is fed to a high-pressure compressor where it is compressed to 6,250 psi (425 atm) for storage and subsequent vehicle refueling. In this configuration, the waste heat that is rejected by the system is available for the building/facility thermal load from three key points: (1) the cooling of the SMR product stream, (2) fuel cell cooling loop, and (3) the fuel cell exhaust stream. The various system-wide power generation and thermal energy efficiency metrics are presented in Figure 2-5.

Efficiencies (parasitics not included)

Reformer carbon conversion efficiency	92.4%
Reformer H ₂ production efficiency	75.4%
Fuel cell efficiency (DC Power/Anode H ₂)	55.8%
Fuel cell efficiency (DC Power/System Energy In)	42.1%
Fuel cell cogen heat efficiency	48.3%
PSA purification efficiency	70%
DC/AC inverter efficiency	90%

Parasitic Loads

Feedstock NG compressor	kWe
Feedstock water compressor	3.0
Combustion air blower	2.5
PSA system motors	0.8
High Pressure Compressor	1.0
Miscellaneous	11.0
	0.5
Total	18.75

Figure 2-5. Configuration 1: Summary of Key Metrics and Conceptual Flow Sheet

Configuration 2: SMR at Ambient Pressure with Hydrogen Fuel Cell

In this configuration, the SMR is operated at ambient pressure. Similar to the SMR reactor system in Configuration 1, it consists of a reformer reactor, an HTS reactor and an LTS reactor. Product from the SMR is cooled and compressed to 10 atmospheres before being fed to the PSA purification system. Following the PSA, the hydrogen is either fed to the fuel cell directly (after

some reduction in pressure), or it is fed to a high-pressure compressor where it is compressed to 6,250 psi (425 atm) for storage and subsequent vehicle refueling. In Configuration 2, as in configuration 1, the waste heat that is rejected by the system is available to the building/facility thermal load from: (1) the cooling of the SMR product stream; (2) fuel cell cooling loop; and (3) the fuel cell exhaust stream. The various system-wide power generation and thermal energy efficiency metrics are presented in Figure 2-6.

Configuration 3: SMR with Reformate Fuel Cell

In this configuration, the fuel cell is powered by reformate product gas directly from the SMR. The SMR reactor is an ambient pressure system and is similar in design to that of Configuration 2. The SMR product gas consisting mainly of CO₂, H₂, H₂O, and N₂ is cooled and compressed to 2-3 atmospheres before being fed to the fuel cell system. If a PSA purification system is being used for storage, then an additional compressor will be required to pressurize the gas to 10 atmospheres as in the case of Configurations 1 and 2. Following the PSA, similar to the steps in the previous two configurations, the purified H₂ is fed to a high-pressure compressor where it is compressed to 6,250 psi (425 atm) for storage and subsequent vehicle refueling. In Configuration 3 the waste heat that is rejected by the system is available to the building/facility thermal load from only two sources: (1) the cooling of the SMR product stream; and (2) fuel cell cooling loop. Unlike Configurations 1 and 2, the fuel cell exhaust stream contains excess hydrogen, consequently has a greater net heating value, and is routed back to the SMR combustor as heating fuel. For Configuration 3, the power generation and thermal energy efficiency metrics are presented in Figure 2-7.

Configuration 4: ATR with Reformate Fuel Cell

In this configuration, the ATR is operated at 10 atm pressure. The ATR reactor system consists of a reformer plus partial oxidation section, an HTS reactor, an LTS reactor and a PrOx to reduce CO in the product gas to trace amounts. In this configuration, the fuel cell is powered by reformate product gas directly from the ATR. The ATR product gas consisting mainly of CO₂, H₂, H₂O, and N₂ is cooled fed to the fuel cell system at 1 to 3 atm. The gas stream can also be fed to the PSA, similar to the steps in the previous configurations, the purified H₂ is fed to a high-pressure compressor where it is compressed to 6,250 psi (425 atm) for storage and subsequent vehicle refueling. In Configuration 4 the waste heat that is rejected by the system is available to the building/facility thermal load from three sources: (1) the cooling of the SMR product stream; (2) fuel cell cooling loop; and (3) the fuel cell exhaust stream. As in the case of Configuration 3, the fuel cell exhaust stream is energetic as it contains excess hydrogen from the fuel cell and has a greater net heat utilization potential than its counterparts in Configuration 1 and 2. However, unlike Configuration 3, the fuel cell exhaust stream is not required by the ATR for heating purposes. Therefore, the fuel cell exhaust stream in Configuration 4 is available to the building/facility thermal load. The various system-wide power generation and thermal energy efficiency metrics are presented in Figure 2-8.

Efficiencies (parasitics not included)

Reformer carbon conversion efficiency	92.4%
Reformer H ₂ production efficiency	75.4%
Fuel cell efficiency (DC Power/Anode H ₂)	55.8%
Fuel cell efficiency (DC Power/System Energy In)	42.1%
Fuel cell cogen heat efficiency	36.2%
PSA purification efficiency	70%
DC/AC inverter efficiency	90%

Parasitic Loads

	kWe
Feedstock NG compressor	
Feedstock water compressor	
Combustion air blower	0.8
Reformate compressor (to PSA); 10 atm	2.5
Reformate compressor (to fuel cell); 2-3 atm	1
PSA system motors	1.0
High Pressure Compressor	11.0
Miscellaneous	0.5
Total	16.75

Figure 2-6. Configuration 2: Summary of Key Metrics and Conceptual Flow Sheet

Efficiencies (parasitics not included)

Reformer carbon conversion efficiency	92.9%
Reformer H ₂ production efficiency	106.6%
Fuel cell efficiency (DC Power/Anode H ₂)	46.4%
Fuel cell efficiency (DC Power/System Energy In)	49.4%
Fuel cell cogen heat efficiency	49.1%
PSA purification efficiency	N/A
DC/AC inverter efficiency	90%

Parasitic Loads

	kWe
Feedstock NG compressor	
Feedstock water compressor	
Combustion air blower	0.8
Reformate compressor (to PSA); 10 atm	0
Reformate compressor (to fuel cell); 2-3 atm	0
PSA system motors	1.0
High Pressure Compressor	11.0
Miscellaneous	0.5
Total	13.25

Figure 2-7. Configuration 3: Summary of Key Metrics and Conceptual Flow Sheet

Efficiencies (parasitics not included)

Reformer carbon conversion efficiency	94.0%
Reformer H ₂ production efficiency	73.4%
Fuel cell efficiency (DC Power/Anode H ₂)	46.3%
Fuel cell efficiency (DC Power/System Energy In)	34.0%
Fuel cell cogen heat efficiency	60.3%
PSA purification efficiency	0%
DC/AC inverter efficiency	90%

Parasitic Loads

Feedstock NG compressor	kWe
Feedstock water compressor	
Combustion air blower	0.8
Reformate compressor (to PSA); 10 atm	2.5
Reformate compressor (to fuel cell); 2-3 atm	1
PSA system motors	1.0
High Pressure Compressor	11.0
Miscellaneous	0.5
Total	16.75

Figure 2-8. Configuration 4: Summary of Key Metrics and Conceptual Flow Sheet

Configuration 5: ATR with Hydrogen Fuel Cell

The ATR system in Configuration 5 is similar to the one in Configuration 4. The main difference is that in this configuration, the fuel cell is powered by hydrogen after being purified by the PSA, as in the cases of Configuration 1 and 2. Following the PSA, the hydrogen is either fed to the fuel cell directly (after some reduction in pressure), or it is fed to a high-pressure compressor where it is compressed to 6,250 psi (425 atm) for storage and subsequent vehicle refueling. In Configuration 5, as in Configurations 1 and 2, the waste heat that is rejected by the system is available to the building/facility thermal load from: (1) the cooling of the SMR product

stream; (2) fuel cell cooling loop; and (3) the fuel cell exhaust stream. The various system-wide power generation and thermal energy efficiency metrics are presented in Figure 2-9.

Figure 2-9. Configuration 5: Summary of Key Metrics and Conceptual Flow Sheet

2.2.3 System Performance

Each of the systems provides some advantages and disadvantages in terms of operating parameters such as:

- Energy consumption

- Operability
- Durability
-
- Building integration

Highest Efficiency for Power Generation

Configurations 1 and 3 (high pressure SMR with hydrogen fuel cell and SMR with reformat fuel cell) provide the highest electric conversion efficiencies among the options analyzed. The high pressure SMR also produces a pure hydrogen stream which can be used directly for vehicle fueling, while the reformat stream requires purification for vehicle use.

Reformat Compressor

Low pressure SMR systems have been built by several developers and represent a less complex mechanical design than the high pressure system. The simpler design comes at the expense of the system requiring a significant amount of power to operate the reformat compressor. This compressor must compress the mixture of hydrogen, CO₂, and CO from the SMR, while the compression work with the high pressure SMR is accomplished by compressing the natural gas and water feed streams. The efficiency penalty and cost of the compressor limits the appeal of Configuration 2 for use in an energy station.

Reformat Fuel Cell

The reformat fuel cell systems require clean-up of the reformat stream before it is fed into the fuel cell. The stream must contain less than ppm levels of sulfur and CO. The CO removal is accomplished first with the LTS reactor which converts CO to CO₂ by reacting with steam. Final CO removal is accomplished with a PrOx reactor, which reacts oxygen (air) with CO. The control requirements and catalyst volume add cost and complexity to these systems. The suitability of the reformat fuel cell systems for energy stations is limited because the hydrogen requires further purification for vehicle use (Configurations 3 and 5). Additionally, maintaining the durability of the PEM fuel cell when fed a stream of reformat is more challenging than operating a direct hydrogen system.

Autothermal Reformer

The ATR system produces a more dilute hydrogen stream than the SMR. The dilute hydrogen stream requires a larger capacity PSA and also affects its efficiency. Unlike the SMR, the waste stream from the PSA is not required as an energy input for reforming; however, some ATR systems use the waste gas to preheat steam and air entering the ATR.

Cogeneration Heat

Heat recovery from the energy station system is challenging because of the quality of the heat and matching heat with building load requirements. Both ATR and SMR systems are thermally integrated and provide little opportunity for waste heat recovery. The most significant sources of waste heat from the energy station systems discussed here include:

- Cooling reformat prior to PSA
- Cooling PEMFC
- Combusting waste gas from ATR/PSA system

Using any of these heat sources provides building integration challenges. Both PSA cooling and ATR waste gas can only be used for heating when the reformer is operating. Integration of the ATR waste gas with an existing boiler is much simpler than performing the heat integration with heat exchangers.

The PEMFC provides waste heat at approximately 80°C. This low level heat may be suitable for preheat with a hydronic heating system or for applications with that operate at low temperatures, primarily swimming pools. If the PEMFC operates in a peak shaving mode, heat from the fuel cell will only be available during its period of operation.

2.3 Emissions Analysis

In order to assess the relative emission benefits of an energy station, we estimated the incremental criteria pollutant and greenhouse gas emissions for each of the representative operating scenarios and configurations described above. These incremental emissions estimates represent the difference between on-site emissions produced by an energy station and those that would be produced by a comparable hydrogen fueling-only station — that is, one with a natural gas reformer and the same hydrogen vehicle throughput, but no CHP. TIAX also estimated the incremental fuel cycle emissions, assuming a California-based energy station. Here, the incremental fuel cycle emissions refer to the incremental emissions associated with extraction, processing, production, and transport of energy to the point-of-use.

The emission factors for on-site emissions were determined from standard emission rates for natural gas boiler operation and estimated emission rates for hydrogen production from natural-gas-powered reformers. The fuel cycle emission factor for electricity production and transmission was determined from a survey of natural gas power plant averages and adjusted to account for the California electrical power mix. The fuel cycle emission factor for natural gas used by energy stations and natural gas power plants was based upon results from the GREET 1.6 model.² Using these on-site and fuel cycle emission factors, the incremental energy station emissions were determined by considering the amount of natural gas and electricity consumed by an energy station and host site relative to a comparable hydrogen fueling station and host site. Figure 2-10 describes the calculation methodology for determining the incremental energy station emissions.

Appendix B contains the detailed emission analysis results for the various operational and configuration scenarios described above. Table 2-3 provides a summary of the incremental emission analysis results, in order to show how the extent of variation between these operational scenarios and equipment configurations.

² TIAX determined the well-to-production criteria pollutant and greenhouse gas emissions for natural gas using GREET 1.6, the “Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model” developed by Argonne National Laboratory. Assumed 7% transmission losses between natural gas production point and power plant/energy station.

Table 2-3. Summary of Incremental Energy Station Emissions from the Representative Operational Scenarios and Configurations

Emissions Reduction Feature	Vehicles per Day	Operating Scenario ^a	System Configuration ^b	ΔNO _x (tpy)	ΔPM (tpy)	ΔGHG (tpy)	ΔCO (tpy)	ΔUHC ^c (tpy)
Most emissions avoided	3	1	4	-0.20	-0.03	-324	-0.38	-2.12
Least emissions avoided	13	2	2	-0.02	0.00	- 45	-0.03	-0.16
Average Emissions Avoided (for each species)				-0.09	-0.01	-140	-0.17	-0.04

^a Operating scenarios defined in Table 2-1 and Figures 2-1 through 2-4

^b System configurations as defined in Table 2-1 and Section 2.2.2

^c Unburned hydrocarbons

The incremental energy station emissions for a specific operational scenario and configuration were determined using Equation 2-1. Clearly, when the incremental emissions are determined to be negative, then the energy station produces fewer emissions than the comparable hydrogen fueling station for that scenario and configuration. In order to determine the emissions for each type of station, the emissions incurred (or avoided) were determined for each component, then added together, as indicated by Equation 2-2. The component emissions calculation was performed separately for the each of the criteria pollutants (i.e, NO_x, CO, unburned hydrocarbons (UHC), and PM) and the most prevalent greenhouse gases (CO₂, CH₄).

For a given component of the energy station, the related emissions were calculated using Equation 2-3. The specific equations for the reformer, boiler, cogeneration systems, fuel cell, and parasitic loads are given in Equations 2-3a through 2-3e, respectively.

The heat recaptured via cogeneration is assumed to displace boiler emissions because the cogeneration heat offsets heat demand on the boiler. Thus, the emissions factor used for the cogeneration is the same as for the boiler, as shown in Equation 2-3c. The fuel cell produces no on-site emissions. It is assumed that displacing utility electricity offsets emissions created at the power plant. Accounting for transmission losses and the average source mix for California electricity, the fuel cycle emissions avoided by operating the fuel cell are calculated using Equation 2-3d. The energy station equipment creates a parasitic electric load, which we assumed to be drawn from utility power. Thus, the parasitic losses contribute to the electricity fuel cycle emissions produced, as shown in Equation 2-3e.

The reformer emission factors were TIAx estimates of in-use reformer emissions. The boiler and power plant emission factors were determined from industry averages. The fuel cycle emission factor for natural gas was based on GREET 1.6 calculations for a natural gas from extraction to production. This estimate was increased by an additional 7% to account for transmission and pumping losses from the natural gas production site to the point-of-use.

Overall, for a given operational scenario and configuration:

$$\boxed{\text{Energy Station Emissions (g)}} - \boxed{\text{Hydrogen Fueling Station Emissions (g)}} = \boxed{\text{Incremental Energy Station Emissions (g)}} \quad (2-1)$$

Where each station's emissions are:

$$\boxed{\text{Component 1 Emissions (g)}} + \boxed{\text{Component 2 Emissions (g)}} + \dots = \boxed{\text{Station Emissions (g)}} \quad (2-2)$$

For each component of Energy Station & H₂ Fueling Station:

$$\boxed{\text{Component } n \text{ Energy Consumption (kWh)}} * \boxed{\text{Component } n \text{ Emission Factor (g/kWh)}} = \boxed{\text{Component } n \text{ Emissions (g)}} \quad (2-3)$$

This yields the following component emission calculations:

$$\boxed{\text{Reformer Natural Gas Consumption (kWh)}} * \boxed{\text{Reformer Emission Factor (g/kWh)}} = \boxed{\text{Reformer Emissions (g)}} \quad (2-3a)$$

$$\boxed{\text{Boiler Natural Gas Consumed (kWh)}} * \boxed{\text{Boiler Emission Factor (g/kWh)}} = \boxed{\text{Boiler Emissions (g)}} \quad (2-3b)$$

$$\boxed{\text{Cogeneration Energy Recovered (kWh)}} * \boxed{\text{Boiler Emission Factor (g/kWh)}} = \boxed{\text{Boiler Emissions Avoided (g)}} \quad (2-3c)$$

$$\boxed{\text{Fuel Cell Electricity Produced (kWh)}} * \boxed{\text{Electricity Fuel Cycle Emission Factor (g/kWh)}} = \boxed{\text{Electricity Fuel Cycle Emissions Avoided (g)}} \quad (2-3d)$$

$$\boxed{\text{Parasitic Power Demand (kWh)}} * \boxed{\text{Electricity Fuel Cycle Emissions Factor (g/kWh)}} = \boxed{\text{Electricity Fuel Cycle Emissions (g)}} \quad (2-3e)$$

Figure 2-10. Incremental Emission Calculation Methodology for an Energy Station Relative to a Hydrogen Fueling Station

Overall, the energy station avoided incremental emissions relative to a comparable hydrogen fueling station for all cases and pollutant species considered. However, certain system configurations and operational scenarios tended to avoid the most emissions. Table 2-4 summarizes the incremental emission trends between operational scenarios and between system configurations.

Table 2-4. Trends in Avoided Incremental Emissions across Representative Operational Scenarios and System Configurations

Avoided Incremental Emissions Among the Various System Configurations ^a					
	Δ NOx	Δ PM	Δ GHG	Δ CO	Δ UHC
Most Emissions Avoided	Configuration 4	4	4	1	4
Similar Emissions	1, 3, 5	1 & 3, 2 & 5	1, 3	1, 3	1, 3
Least Emissions Avoided	2	2, 5	2, 5	5	2
Avoided Incremental Emissions Among the Various Operational Scenarios ^a					
	Δ NOx	Δ PM	Δ GHG	Δ CO	Δ UHC
Most Emissions Avoided	Scenario 1 for virtually all cases ^b				
Similar Emissions	1 & 2, 3 & 4; 1 through 4 are similar for 13 vehicles per day				
Least Emissions Avoided	3 for 3 and 7 vehicles/day cases, 2 for 13 vehicles/day case				
Avoided Incremental Emissions Among the Various Vehicle Throughput Scenarios					
Most Emissions Avoided	3 vehicles per day for all cases				
Least Emissions Avoided	13 vehicles per day for all cases				

^a See Table 2-1 for numbering conventions. Corresponding Configuration or Scenario numbers given.

^b For System Configurations 2 or 5, with 3 vehicles a day, Scenario 2 provides the most avoided GHG and UHC emissions.

In general, when compared to a comparable hydrogen fueling-only station, an energy station provides additional electricity and process heat to the nearby facilities while emitting fewer emissions. The incremental emissions avoided by using CHP at the energy station scales with fuel cell and cogeneration use, thus the avoided emissions are highest when most of the hydrogen is directed to the fuel cell. This relationship is depicted in the figures within Figure 2-11, with the highest avoided incremental emissions occurring when the fewest cars are refueling.

As shown in the chart on the left panel of Figure 2-11, when vehicle throughput increases, the incremental emission benefits decrease because hydrogen is diverted away from the fuel cell to fueling vehicles. However, even when fuel cell operation is minimal, the cogeneration system continues to reclaim waste heat from the reformer system and thereby continues to displace incremental emissions. As indicated in the right panel of Figure 2-11, larger capacity reformer/fuel cell systems can provide greater incremental emission benefits due to the increased availability of fuel cell electricity and cogeneration heat.

NOTE: Both figures use the “Most Emissions Avoided” case from Table 2-1: Operating Scenario 1, System Configuration 4, and 50 kWe reformer and fuel cell capacity (except where noted). Assuming 5 kg/fill, up to 13 vehicles/day can be fueled with a 50 kWe reformer system, 20 vehicles/day with a 75 kWe system and 26 vehicles/day with a 100 kWe system.

Figure 2-11. Dependence of Avoided Emissions on Vehicle Throughput and Reformer/Fuel Cell Capacity

2.4 Cost Analysis

For the costs analysis, TIAX used an in-house energy station cost model that scaled known energy station equipment costs by volume produced (annually) and by key operational parameters (such as flow rate, power output, etc.). This model allowed us to determine the equipment costs of an energy station relative to that of a hydrogen fueling station.

Cost estimates were based on parameters for fuel cell systems shown in Figures 2-12 and 2-13. The cost of PEM fuel cells was based on TIAX cost model projections as a function combined with near term cost data based on discussions with developers. The costs of both the membrane material as well as complete stacks are shown.

Figure 2-12. Fuel Cell Membrane Electrode Assembly Costs.

Figure 2-13. Fuel Cell Membrane Electrode Assembly Costs.

The costs of fuel cell systems will decline as production volumes increase as illustrated in Figure 2-14. PEM energy station capital costs were estimated for systems corresponding to annual fuel cell production volumes of 50 MW per year or the equivalent of 1000 fuel cell cars.

Figure 2-14. Fuel Cell Membrane Electrode Assembly Costs

The capital costs for an energy station system for the 5 options analyzed in this report are shown in Figure 2-15. These costs include the following components:

- PEM fuel cell
- Balance of fuel cell system and power electronics
- Reformer
- Balance of system, controls, heat integration with the building
- Site work

Figure 2-15. Fuel Cell Membrane Electrode Assembly Costs

The capital costs of the energy station systems were very similar. At the 50 MW fuel cell production volume, we believe that developer will have achieved a successful development of the Configuration 1 energy station with the high pressure steam reformer. Figure 2-16 shows how the incremental cost of a PEM fuel cell and heat recovery system would affect the economics of an hydrogen fueling station. In the initial years of fuel cell vehicle operation, a fueling station would not expect to operate at a high capacity factor. Figure 2-16 illustrates the incremental cost and revenue associated with power production and heat recover.

Figure 2-16. Fuel Cell Membrane Electrode Assembly Costs

The relative costs of operating an energy station versus a hydrogen fueling station were also determined. The relative operating costs were determined by assessing the baseline unit cost of producing heat and electricity for the host facility, and comparing that to the cost of producing heat and electricity via the energy station. At high production volumes (over 100,000 fuel cell vehicles per year) and 500 hydrogen fueling stations per year, the energy station can approach cost parity with grid power as illustrated in Figure 2-17. The complete set of results are given in Appendix B along with the assumed price for electricity and natural gas used in the analyses.

Figure 2-17. Fuel Cell Membrane Electrode Assembly Costs

3. Exploring Public and Private Partnerships (Task 6)

In developing partnerships for energy station development, TIAX's resources included various public agency and private sector contacts. To develop a partnership with a federal facility, personnel at national laboratories, military facilities, the Postal Service, the General Services Administration, the Departments of Energy, Defense, and Interior (National Park Service), and the Veterans Administration were contacted. TIAX also developed a partnership with a major supplier of reformer and fuel cell components. Additional contacts were made using resources from various technical meetings and professional conferences.

3.1 Review of Potential Federal Facility Host Sites

TIAX investigated the potential sites identified in the Phase I report. Based on recommendations from TIAX's subcontractor, TIAX focused its partnering efforts on a National Park Service park and a US military facility. Both of these potential partners have existing alternative fuel applications or interests. They also have vehicle fleets and facilities with power and heating demands.

The park, the Presidio of San Francisco, is part of the Golden Gate National Recreation Area and is operated by the National Park Service and the Presidio Trust, a public/private agency. The Presidio was an Army facility for approximately 150 years up until its conversion to a park in 1994. The park covers nearly 1,500 acres with hundreds of individual buildings and roads. Two buildings identified as potential energy station sites were the main post/administrative building and a hospital, currently unoccupied. Both facilities have electricity and hot water demands. The Presidio also has an alternative fuel fleet consisting of 45 CNG F150 pickups, 15 electric cars, 10 electric RAV4s, and 30 electric Th!nk vehicles. The buses and EVs are refueled/recharged outside the main post. With both building and vehicle demands, the facility could have energy station potential.

Due to a variety of factors, however, the transportation and energy managers at the site decided they were not interested in hosting a facility at the time of this study. One reason was that the main post already housed a 30 kWe Capstone turbine, with the turbine exhaust routed through a heat recovery steam generator (HRSG). The HRSG is used for a 7 MMBtu/hr hydronic heating loop for the main post building, with the water entering the HRSG at 140°F and exiting at 190°F. Because the cost of generating electricity with the turbine is higher than the local utility's government purchase price, the turbine is rarely utilized. Instead, the HRSG is normally directly fired with a natural gas burner. There was some concern that an energy station would have the same price competition barriers as the Capstone turbine.

Another factor that made the project less attractive for the Presidio was their preference for a solid oxide fuel cell installation, if the Presidio were ever to host a fuel cell technology demonstration. Also, the facility already had invested in a large number of natural gas and electric vehicles along with their respective fueling infrastructure. Embarking on a different type of distributed generation and a new vehicle fleet and fueling infrastructure wasn't the right option at the time.

The second facility considered was a military facility, Port Hueneme near Ventura, CA. This facility also fit the criteria for a potential host site. The Port Hueneme military facility is part of the Naval Sea Systems Command. The facility provides engineering and logistical support to the US naval fleet (See Appendix C).

The facility had several sites that could be appropriate for an energy station. These included the Port Hueneme Pool, which is slated for a 60kW Capstone turbine and the main entry building, Building 850, which has a 25kW rooftop PV installation and serves as a destination for facility tours and meetings with high ranking personnel. The electricity demand in Building 850 exceeds the PV supply on sunny days, making it a good site for peak shaving. The base has proposed building a biodiesel production facility near Building 850 that could use hot water and electricity from the energy station.

Port Hueneme also has interest and experience in alternative fuel vehicles. The facility currently operates a few natural gas vehicles but at one time had more than 200. It also owns flexible fuel vehicles, which it depends on to meet alternative fuel vehicle requirements. The transportation manager has expressed interest in procuring hydrogen fuel cell vehicles and the facility has proposed testing vehicles from US auto manufacturers.

The managers of this site continue to be interested in an energy station venture. To illustrate their interest, TIAX and Port Hueneme formed a partnership in proposing to the California Energy Commission an evaluation of enhanced heat recovery using an energy station.

3.2 Potential Partners

A variety of partners could be helpful in developing an energy station. Table 3-1 shows several types of public and private partners and their role in the project. The focus for these partners is a demonstration or near-term energy station.

3.2.1 Criteria for Partnering

Finding the right partners will enable a energy station to be sufficiently funded, sited, and fitted with the proper equipment. Table 3-2 shows criteria TIAX developed for choosing project partners.

3.2.2 Interested Potential Partners

In addition to Port Hueneme, which has been enthusiastic in partnering with TIAX, several other potential partners were approached. TIAX contacted several oil/energy, natural gas, and power companies. Most of these companies are interested in the energy station concept but have not entered into any partnering agreements at this time.

TIAX has also contacted manufacturers of equipment for the energy station. Hydrogenics, maker of fuel cell equipment and a leader in integration of hydrogen/fuel cell systems, has expressed interest in helping to develop an energy station. Like Port Hueneme, Hydrogenics has participated with TIAX in a proposal to evaluate the heat recovery from an energy station. In addition, Harvest Energy Technologies, maker of steam methane reformers, is a partner.

Table 3-1. Key Types of Public and Private Partners

Partner	Project Role
Sites	
Federal building(s)	The buildings provide the load for the fuel cell electricity and hot water. The siting and sizing is determined with the building manager or energy manager
Equipment Manufacturers	
Fuel cell/reformer/compressor manufacturer	Provides integrated fuel processing and power production system
Fuel dispenser manufacturer	Provides dispenser for fueling vehicles with hydrogen and connectors to storage system
Utilities	
Gas	Negotiate rate structures, consult and provide any alterations to gas lines required
Electricity	Negotiate rate structures, interconnectivity
Local Organizations	
Local permitting agency	Review and approve plans
Air quality agency	Determination if air quality permit required for reformer
City or County	Obtain community support for project
Existing hydrogen public/private partnerships	Provide technical and policy support on hydrogen infrastructure
Fleets	
On-site federal fleet	Fleet manager works with facilities to determine fueling capacity, siting issues
Off-site public or private fleet	Off-site partner helps to determine same issues as on-site fleet plus access and payment
Grant or Funding Organizations	
Federal, state, or local funding organization with interest in hydrogen infrastructure, fuel cells, or transportation	Provide cost share for project

Table 3-2. Criteria for Choosing Partners

Partner	Criteria
Sites	
Federal building(s)	<ul style="list-style-type: none"> • Electricity load • Hot water demand • Natural gas delivered to site • Location convenient for on- or off-site fleet • Capable of interconnectivity • Available footprint for installation
Equipment Manufacturers	
Fuel cell/reformer/compressor manufacturer	<ul style="list-style-type: none"> • Integrated unit • Required footprint matches offerings • Able to participate in cost-share
Fuel dispenser manufacturer	<ul style="list-style-type: none"> • Hydrogen-specific equipment • Dispenser type matches needs of fleet (may be different for on-site or off-site fleet)
Utilities	
Gas	Attractive rates
Electricity	Attractive rates, cooperation with interconnectivity
Authority with Jurisdiction	
Local permitting agency	Favorable towards hydrogen installations, experience with hydrogen fueling or fuel cells
Air quality agency	Does not present barriers to reformer installation
City or County	Is interested in siting the project in the area
Fleets	
On-site federal fleet	Small hydrogen-fueled fleet
Off-site public or private fleet	Small hydrogen-fueled fleet operating in close proximity to energy station

Other potential partners include existing public/private partnership organizations that are already working in the area of hydrogen and fuel cells. In California where the Port Hueneme site is located, two such organizations exist: the California Fuel Cell Partnership and the Stationary Fuel Cell Collaborative. In addition, recent interest by California government officials to build a “hydrogen highway” linking major highways with hydrogen fueling stations has generated a call for a new public/private partnership. Other states also have existing hydrogen or fuel cell organizations. For example, the Florida Hydrogen Partnership is a focal point for hydrogen industry development and brings together government, universities, and the private sector to achieve its goals. These types of organizations can be very helpful in providing collaborative knowledge and experience to a project, even if no funding is available.

3.3 Existing Energy Station Plans and Evaluation of Success

Few energy stations like those studied for this report currently exist or are in the planning phases. A review of three related projects underway indicates that the extent of public and private partnerships depends on the project scope.

A project in Las Vegas with partners such as Air Products and Chemicals, Plug Power, and the City of Las Vegas has approached the fueling station development process through a concept, which they have also referred to as an energy station but which is somewhat different from this study's concept. In the Las Vegas project, a fuel cell power plant provides base-load electricity with incremental capacity used for hydrogen fueling (NAS 2003). The hydrogen is produced on-site with supplemental or back-up hydrogen delivered as liquid hydrogen. The project also uses a blend of hydrogen and CNG or pure hydrogen in the fueling aspect of the system (Raman 2002). The Las Vegas project differs from the energy station designs in this report in that the electricity is not dedicated to an on-site facility and the project does not make use of rejected heat from the power plant.

One result of note from the Las Vegas project is that Air Products initially planned to use an ATR for producing hydrogen. After an economic analysis, the project managers decided that SMR technology was more economical for the 50kW size range. Harvest Energy Technologies became the SMR partner for the project, which became operational in November, 2003. The ATR vs SMR finding is consistent with this report's conclusion that SMR is the best reforming technology for a 50 kW energy station application.

Honda has also investigated the energy station concept with a Home Energy Station, which it began testing in October, 2003. This demonstration is closer to the energy station concept researched in this report. The Honda project uses a reformer to produce hydrogen from natural gas and produces electricity and hot water for a home. Plug Power is the strategic partner for the fuel cell. The Home Energy station supplies enough hydrogen to refill the tank of Honda's FCX (fuel cell vehicle). Due to Honda's system being an experimental project on its own site with its own vehicles, it has not needed an extensive network of partners in order to develop the project.

In addition to energy stations, DOE is also supporting efforts in a concept called power parks. These are similar to energy stations in the distributed generation concept but do not necessarily use rejected heat or store hydrogen for fueling. The public/private partnerships developed for construction of hydrogen power parks are likely to be similar to energy station partnerships. An ongoing project in Hawaii has an extensive network of public and private partners that are sharing costs and providing expertise and equipment (Kaya 2003). The project expects to build a 5 kW PEM fuel cell using hydrogen from renewable resources with an option for vehicle refueling.

It is difficult at this time to measure the success of these or other projects related to energy stations due to the very recent efforts in these areas. Energy stations, as defined in this report to have combined heat, power, and fueling, seem to be rare at this time. Nevertheless, as the projects in Table 3-3 move forward, more will be known about the keys to success in developing partnerships for hydrogen distributed generation and the integration of hydrogen fueling. Knowledge about the challenges of integrating system heat into distributed generation and fueling projects will require evaluation of projects that have not yet been realized.

Table 3-3. Partnerships Developed for Similar Types of Hydrogen Projects

Project	Description	Project Status	Public Partners	Private Partners
Las Vegas Integrated Fuel Cell/Vehicle Fueling	Combined power, vehicle fueling using NG reformer	5-year public demo	<ul style="list-style-type: none"> • DOE (cost share for vehicle conversion) • City of Las Vegas 	<ul style="list-style-type: none"> • Air Products and Chemicals • Plug Power • Harvest Energy Technologies • QuestAir Technologies
Honda R&D America Home Energy Station	Combined heat, power, vehicle fueling using NG reformer	R&D demo	<ul style="list-style-type: none"> • Honda R&D 	<ul style="list-style-type: none"> • Plug Power
Hawaii Hydrogen Power Park	Power with possible vehicle fueling using renewable energy and electrolyzer	In design phase with some components received, first permitting complete	<ul style="list-style-type: none"> • State of Hawaii Department of Business, Economic Development & Tourism (DBEDT) • DOE • CEC • Sandia National Laboratory 	<ul style="list-style-type: none"> • Hawaii Natural Energy Institute • Sentech • UTC Fuel Cells • Hawaii Electric Light Company • Hawaii Electric Company • Stuart Energy • SunLine Services

4. Identification of Barriers to Hydrogen Use (Task 7)

An energy station installation faces several challenges including costs, building codes and equipment standards, distributed generation issues, and the public perception issues that are faced by nearly any hydrogen technology. In addition to barriers to installing a system, initial problems include buildings with inappropriate loads and vehicle refueling requirements, sites that are too small, desires for only renewable fuels, and misinformation about fuel cell efficiencies. These initial issues were identified during TIAX's investigation of potential locations and partnerships for building energy stations.

Assuming that a proper site for an energy station is identified and the fuels and fuel cell types are agreed upon, the project may still face barriers due to the costs, some building codes and equipment standards, distributed generation issues, and public perception issues. This section discusses these three areas.

4.1 Cost Barriers

4.2 Building Codes and Equipment Standard Barriers

The following discussion on codes and standards only addresses codes presenting potential barriers (issues that could be show-stoppers) and minimal barriers (issues that continue to be raised in discussions but should not be considered show-stoppers). Codes and standards that do not present a barrier are not discussed.

Energy stations are composed of three main systems, the hydrogen production, the stationary fuel cell, and the hydrogen fueling station, all of which can be and have been successfully installed according to existing codes. The codes, however, do present some challenges for energy station installations that may be different from a fueling station or fuel cell alone. The discussion of barriers relating to codes can be split into two parts: barriers associated with fuel cells with on-site hydrogen production, and those related to hydrogen fueling stations.

One source of information for this discussion is a draft paper developed through an ongoing, collaborative effort between government and private organizations to provide guidance in permitting hydrogen technologies.³ Although a draft version was used for guidance in developing this discussion, all information described is available in final, published documents written by various organizations that develop codes and standards. In addition, these codes and standards continue to change at a rapid pace due to the evolving development and implementation of hydrogen and fuel cell technologies. The reader should assume that the most recent documents may have more information than what is written here.

³ Collaborative effort of the National Fire Protection Association, the International Code Council, Pacific Northwest National Laboratory, and the National Renewable Energy Laboratory. "Regulators' Guide to Permitting Hydrogen Technologies." DRAFT. Sep. 2003.

The main sources of code information relevant in the United States and referenced here are the National Fire Protection Association (NFPA), the International Code Council (ICC), and the American Society of Mechanical Engineers (ASME). The ICC publishes the International Fire Code and the International Mechanical Code, both of which contain relevant guidance. In addition, Underwriters Laboratories (UL) and the American National Standards Institute (ANSI) develop standards for equipment used in fuel cell and fueling stations.

4.2.1 Stationary Fuel Cell Installation with Hydrogen Production

Building codes for stationary fuel cells require attention in the following areas:

- Siting
- Fuel production, storage, and waste
- Equipment
- Ventilation
- Fire protection
- Electrical interconnection

The main code for installation of stationary fuel cell power plants is NFPA 853. The code covers system design (Ch. 2), siting and interconnections (Ch. 3), fuel supplies and storage (Ch. 4), ventilation and exhaust (Ch. 5), and fire protection (Ch. 6). Most issues in NFPA 853 do not present barriers to energy station installations as they present the same types of requirements as other power production or industrial installations. There are, however, a few specifications in NFPA 853 and other codes that present barriers for energy stations or are worthy of mention. These topics are discussed in Table 4-1.

4.2.2 Codes related to the fueling station, including storage

Building codes for hydrogen fueling stations require attention in the following areas:

1. Station siting issues
2. Storage
3. Station equipment and piping
4. Fire protection
5. Operation and Maintenance

The only code written specifically for hydrogen vehicle fueling facilities is the International Fire Code (IFC) Section 2209. Gaseous hydrogen storage guidance can also be found in NFPA 50A. Table 4-2 shows the potential barriers related to the installation of the fueling equipment and hydrogen storage.

Table 4-1. Barriers to Fuel Cell Installation with Reformer

Category	Barrier	Source for Reference
Siting		
General Issues	Potential barrier: requires protection from the elements including flood and earthquake. Some interpretations of this code could limit the siting of an energy station.	NFPA 853 Ch. 3-1
Roof and outdoor locations	Minimal barrier: roof mounting of fuel cells is possible but must comply with outdoor codes like exhaust distance separations, flammability of surrounding area, and flammability of roofing materials. Also must be accessible for maintenance. Storage of the hydrogen on the roof is a separate issue not addressed in NFPA 853 or NFPA 50A.	NFPA 853 Ch. 3-4, NFPA 70
Fuel Supply, Storage, Waste		
Natural Gas	Minimal barrier: natural gas piping and components must satisfy existing codes	NFPA 853 Ch. 4-2, IFC, NFPA 54
Hydrogen Storage	Storage of hydrogen is not necessary for a fuel cell but is required for the fueling station aspect of the energy station. Barriers are discussed in the fueling station section.	
Wastewater	Potential barrier: if condensate is produced by the fuel cell or other equipment, provisions must exist to dispose or recycle it.	ICC (mechanical code 307 and plumbing code 301.3 App. 3)
Pressure Vessels	Minimal barrier: pressure vessels must be approved for hydrogen and/or natural gas use	ASME Boiler and Pressure Vessel Code
Fire Protection		
Fire hydrant	Potential barrier: if hydrogen is stored on-site, fire hydrant protection is required	NFPA 853 Ch. 6-1, NFPA 30
Equipment		
Equipment	Minimal barrier: all equipment and accessories need to be recommended for hydrogen use.	NFPA 50A Ch. 2
Electrical Interconnections		
Utility Interconnect	Potential barrier: local, state, or utility codes may require significant equipment and costs	Codes specific to site, electric utility

Table 4-2. Potential Barriers to Fueling Station Installation

Category	Barrier	Source for Reference
Siting		
General Issues	Potential barrier: storage must comply with minimum separation distances and outdoor exposure requirements	NFPA 50A Ch. 3-2, IFC Sect. 2209.3.1, IFC Sect. 3504.2.1
Storage		
Pressure Vessels	Minimal barrier: tanks must be approved for permanent storage of hydrogen. Some DOT storage containers may not be eligible for permanent stationary storage. Evolving codes for storage tank materials should be consulted.	ASME BPVC Sect VIII, NFPA 50A Ch. 2-1
Structural support	Minimal barrier: pressure vessels must be permanently installed with non-combustable materials and support and secured against accidental dislodgement. This is included as a barrier because some past fueling stations have used non-permanent designs.	NFPA 50A Ch. 2-1
Hazardous conditions	Minimal barrier: tanks must be separated above other storage or piping of combustible materials. Tanks must not be exposed to a potentially failed power line.	NFPA 50A Ch. 3-1
Fire Protection		
Hazardous conditions	Minimal barrier: fueling equipment must be separated above other storage or piping of combustible materials. Tanks must not be exposed to a potentially failed power line.	NFPA 50A Ch. 3-1
Operation and Maintenance		
Training	Potential barrier: training is required for people using the fueling station.	IFC Sect 2209.4, Sect 406, NFPA 5000

4.3 Policy Barriers and Opportunities

The Phase I report indicates that there are several tax provisions and policies that encourage the purchase and use of alternative fuel/low emission vehicles and the installation of fueling infrastructure. The policies and tax provisions vary from manufacturer sales requirements to tax deductions for vehicle purchase. Although they may encourage the use of hydrogen vehicles and fueling facilities, there are no policies or tax provisions that favor an energy station over a fueling-only station. As a result, policies and tax provisions are not likely to play a more active role in energy station development than other hydrogen fueling development.

Although vehicle and fueling policy and tax provisions alone may not exclusively encourage energy station development, the combination of these policies with distributed generation or CHP incentives could tip the scales toward energy stations from fueling-only stations or fuel cells for buildings. However, such incentives for natural gas distributed generation are not widely available. Currently, policies and tax provisions only benefit distributed generation using

renewable energy, such as wind turbines or photovoltaic technologies. As a result, there are currently no DG policies that can be combined with vehicle or fueling policies to encourage the development of natural gas-based energy stations. This does not present a barrier to energy stations but does indicate a gap in incentives between renewable technologies and fossil fuel cell technologies. Nevertheless, energy stations using electrolyzers and renewable technologies would be eligible for such incentives.

Policy gaps may also include incentives that encourage only particular energy production technologies or favor particular fuels. For example, if a local funding agency has a policy to fund only natural gas fueling stations, it will be challenging to seek funding from that agency for hydrogen. Education of policymakers can help close the gaps and lead to expanded funding opportunities.

Interconnection policies also affect the viability of energy stations. This issue is discussed in Section 4.3.1.

4.3.1 Fuel Cell Distributed Generation Systems – Grid Interconnectivity Issues

Interconnection is the linking of on-site generation to the electric utility's distribution grid. It requires the customer and utility to install a variety of relays and monitoring devices on the customer's premises and at the connecting distribution lines, to ensure stability and protection of the grid and protection of the customer's site and generation. The complexity and costs of the interconnection tend to increase with the scale of the on-site generation project. The costs of interconnection at the customer's site and required upgrades to the distribution system are typically paid for by the customer.

The key components of a grid-interconnected fuel cell are shown in Figure 4-1 below. Interconnection of a hydrogen fuel cell to the local grid does not pose any new challenges than the existing ones for interconnection. Photovoltaic systems (solar power) have preceded fuel cells in laying much of the basic framework for DC-generated power interconnection. However, a number of issues still remain and are discussed below under two categories – technical issues and non-technical issues.

Figure 4-1. Key Components of a Fuel Cell Grid Interconnection System

Technical Issues

Most existing utility electric power systems are not designed to accommodate generation and energy storage at the distribution level. The utility is still responsible for voltage and frequency of all its customer connections. Creating an islanding effect where some utility customers are supplied with uncontrolled voltage and frequency is unacceptable. While at a low level of penetration of fuel cell based DG systems may not pose a serious problem to the grid, large-scale penetration will require a concerted effort to develop standards and design/engineer/manufacture standardized components.

IEEE's P1547 is the standard for interconnecting distributed resources with electric power systems and provides the basis for connecting distributed resources to electric power systems. To achieve the goal of developing a streamlined system for interconnection, Underwriters Laboratories (UL) is revising an existing standard, UL1741, to include distributed generation. The revised standard will be called "The Standard for Inverters, Converters, and Controllers for use in Independent Power Systems." The updated standard is aimed at facilitating a means for utility-interconnected DGs to be designed, produced, evaluated, certified, sold, installed, and operated in a manner agreeable to all stake holders.

Non-technical Issues

The importance of DG control by the utilities cannot be under-emphasized. Nearly all utilities in the US require complete control of interconnected DG. The conventional T&D systems of a utility is highly integrated and disruption to this connectivity can have far-reaching consequences as was recently evidenced through the summer of 2003 blackouts in the north-eastern United States and in Italy. Currently, the technical requirements for interconnection vary by state and utility. While the lack of uniform national standard requirements and tests for Dg interconnection, operation and certification are well understood, still some lead time is required for the development of these standards and promulgate their acceptance.

Standardized technical requirements tend to lower the cost of manufacturing of component systems and provide greater product and service quality. Safety is another important benefactor of standardization.

Currently the cost of interconnect systems, specifically the power electronics is a significant percentage of the overall installation. Mass penetration of DG systems will surely bring the cost of interconnection from the \$1,000-\$1,500/kW range to \$10-\$50/kW range.

Economic Viability

A final aspect to DG interconnection success is rate and cost issues. Sophisticated standardized energy management and control programs will be required to balance load and set rates dynamically for DG to be profitable for all stakeholders. An important argument for the proliferation of DG is that utilities can defer the costs of T&D upgrades and extensions.

4.4 Public Perception Barriers

There are two main categories of public perception barriers to energy stations: 1) hydrogen safety concerns and 2) energy station performance (efficiency and costs).

The safety concerns are the same as those that are faced by nearly all non-industrial hydrogen storage and fueling projects. Table 4-3 summarizes some of the public perception issues regarding safety. One method for educating the public is to develop brochures or FAQs on websites that can answer questions and demystify safety hazards and precautions. For an energy station installation in a public area, a local partner like a city or county, is an asset for disseminating safety information to the community.

Table 4-3. Topics of Public Uncertainty Regarding Safety of Hydrogen

Topics
Risks of hydrogen storage and use in residential or commercial areas
Risks regarding hydrogen transported by or stored in vehicles
Consequences and prevention of hydrogen leaks or explosions
Risks regarding earthquakes and other natural disasters
Susceptibility to sabotage
Comparison of hydrogen and gasoline hazards
Uncertainty regarding historical incidents involving hydrogen

Organizations that provide educational materials on hydrogen safety include: National Hydrogen Association, U.S. Fuel Cell Council, DOE's Fuel Cell and Infrastructure Technologies Program, California Fuel Cell Partnership, and California Energy Commission. These organizations have presentations or materials that can be used in educating the public about hydrogen safety. In addition, TIAX has written a technical document for the California Energy Commission on failure modes and effects for hydrogen fueling infrastructure (Venkatesh 2003). These technical results can be paired down to an approachable hydrogen safety reference. Despite these resources, many people receive their hydrogen knowledge from media headlines, which may not present a balanced, educated story. Public perception issues will need to be addressed on a case-by-case basis for most projects in the near future.

The second area of public perception barriers is related to performance and technology issues. Table 4-4 shows some topics associated with these types of barriers.

One benefit of energy stations over distributed electricity generation is the additional aspect of fueling. With more education of potential partners and sites, an energy station concept may be able to overcome the issues of cost-effectiveness, efficiency, and low desire for back-up power. Still, facility modifications do have costs and efforts associated with them. One solution is to partner with organizations that have multiple sites to replicate the project. An example is a company or agency with several offices. In this case, a general plan can be developed for the partner with modifications for each site. Another method to overcome the perception barriers is to involve architects, contractors, or builder associations that are educated about energy stations

Table 4-4. Public Perception Barriers Regarding Energy Station Performance

Barriers
Distributed generation may not be cost-effective or barely cost-effective
Distributed generation requires significant effort
Distributed generation may require facility modifications
Back-up power is not worth the cost and effort – risk of power loss is not high enough to invest in distributed generation
Energy stations aren't the most efficient distributed generation option
Each energy station must be designed individually

and are willing to suggest them to their clients. In addition, many companies and agencies are looking for favorable ratings from green building or energy efficient building organizations. The potential for a high rating and the associated positive media and community attention may help drive the energy station concept for new buildings.

4.5 Areas Requiring Additional Research and Development

4.5.1 Hydrogen Production and Distribution Technology

Hydrogen production has several needs for improvement in order to become more cost-competitive with conventional fuels. Lowering the cost of materials and equipment and raising production volume will aid in reducing the overall system cost. Technical advances are needed to bring about these reductions in cost, and increased hydrogen yield. Improving the use of renewable energy resources to generate hydrogen will help reduce petroleum dependency in the long-term.

4.5.2 Hydrogen Codes and Standards

Hydrogen codes and standards are rapidly being developed and revised to address new types of equipment and new applications of equipment for hydrogen infrastructure. As a result, any document discussing building guidance or equipment standards, including this one, is likely to be dated or possibly obsolete by the time of publication. Further work on the energy station concept or development of a project must take into account the latest information regarding codes and standards. Upcoming changes include NFPA, ICC, ASME, and other guidance documents. NREL, the National Hydrogen Association, and the US Fuel Cell Council are good resources to consult for the latest developments as they are each involved in the hydrogen codes and standards process.

4.6 Cost to Develop Hydrogen Infrastructure

We determined the cost of a single energy station using the TIAX energy station model. The estimated energy station cost was \$140,000 per station (not including siting costs), for 10,000 stations. In order to provide sufficient coverage for on-road hydrogen, TIAX also estimated the number of stations needed to assure a reasonable distribution of stations along major transportation corridors. This estimation assumes a target distribution of one station every 20

miles, in accordance with the California “Hydrogen Highway Network” concept announced by California governor Arnold Schwarzenegger

Proportion of Costs Likely Supported by the Government

In order to effectively promote the development of hydrogen infrastructure throughout the U.S, the government will need to offer support, at least in the short term. However, much of the infrastructure development could be accomplished through incentives and cost-shared programs, with a strong emphasis on commercial funding. The cost of these incentives and programs could vary depending upon the policies and strategies of local, state and federal agencies. In order to be competitive with conventional fuel, hydrogen will need to be provided to the public at a price that matches that of conventional fuel (i.e., gasoline for light- and medium-duty vehicles, and diesel for heavy-duty trucks and buses

5. Conclusion

A detailed analysis of PEM hydrogen energy stations was conducted with the goals of assessing the cost and performance of different energy station options and advancing the opportunities of public/private partnerships to support energy stations. The following conclusions can be drawn from the efforts in this project:

- The high pressure SMR with direct hydrogen PEMFC is the most cost effective and energy efficiency configuration when both the requirements for fuel cell power and hydrogen production are taken into account. The high pressure SMR operates without a reformatte compressor, which reduces cost and parasitic load. Operating the PEMFC on pure hydrogen also leads to a potentially more durable system than operating the PEMFC on reformatte.
- The incremental cost of generating power from a PEM fuel cell is relatively low for an energy station that is intended for hydrogen vehicle fueling. The PEMFC system would be cost effective when fuel cell manufacturing volumes increase.
- Developing partnerships for a PEMFC energy station project has proven challenging for a variety of reasons. First the lack of hydrogen vehicles results in a wait and see attitude with potential operators of energy stations. Secondly, the potential energy efficiency of a PEMFC energy station is about the same as many gird-based natural gas plants. Also, finding a thermal load to match the PEMFC system is difficult since most of the waste heat is produced at low temperature. Finally, the potential efficiency of solid oxide fuel cell systems is expected to be over 35 percent with high level waste heat. Energy station partners were interested in examining the solid oxide fuel cell option. Operators of energy stations also did not perceive a value of electric power greater than \$0.1/kWh even though the PEMFC could be used for peak shaving applications where power costs can be higher.
- While the PEMFC energy station faces challenges, electric power can be produced along side hydrogen for vehicle fueling at a relatively low incremental cost once fuel cell production volumes increase. Siting energy stations with customers that value peak shaving capability or other premium power features associated with PEMFCs can make the hydrogen energy station more attractive than a dedicated hydrogen fueling station.

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Appendix A. Energy Station Process Flows

Configuration 1 — Detailed Process Flow Table — High Pressure SMR, Direct H₂ Fuel Cell

Design Basis		Inputs
Purified hydrogen from PSA	kg/hr	2.96
Fuel cell electricity out	kWe	55
Reference Temperature	Deg. C	40

Process Streams		Mass Flow, kg/hr								T °C	P Atm	HV Btu/lb	kW	Sen Heat kBtu/h	kW	Total kW	
		CH ₄	O ₂	N ₂	H ₂ O	H ₂	CO ₂	CO	UHC								Total
1	Reformer feed natural gas	8.71		0.26			0.18		0.26	9.39	25	1.5	-21537	131	0	0	130.6
2	Reformer feed water/steam				24.44					24.44	25	10		0	0	0	0.0
	Feedstock preheat													131	151.7	44	175.1
3	Combustion air for reformer		13.76	45.29						59.05	200	1		0	9.1	3	2.7
	Reformer product gas (hot)			0.26	10.37	3.71	10.02	8.82	0.66	33.84	800	10	-7216	158	75	22	179.5
	HTS out			0.26	6.14	4.19	20.35	2.24	0.66	33.84	400		-7093	155	36	11	165.5
	LTS out			0.26	5.78	4.23	21.23	1.68	0.66	33.84	250		-7083	155	21	6	160.9
4	SMR Out (Heat removed from LTS out for preheat)													0		0	0.0
5	SMR product gas (cold) to PSA purifier			0.26	1.38	4.23	21.23	1.68	0.66	29.44	40	10	-8142	155	0	0	154.7
6	PSA purifier product hydrogen to compressor				1.10	2.96				4.06	40	10	-37593	99	0	0	98.5
7	Compressed hydrogen to storage					2.96				2.96	30	245	-51605	99	0	0	98.5
8	PSA purifier product hydrogen to fuel cell					2.96				2.96	40	10	-51605	99	0	0	98.5
9	PSA residue gas as fuel to SMR combustor			0.26	0.28	1.27	21.23	1.68	0.66	25.38	200	10	-3429	56	6.3	2	58.0
10	SMR combustor product gas (hot, before preheating feedstock)			45.55	13.18	0.00	25.70	0.00	0.00	84.43		1		0	192	56	56.2
11	SMR combustor exhaust gas (stack)			45.55	13.18	0.00	25.70	0.00	0.00	84.43	117	1		0	6	2	1.9
13	SMR product gas knock-out water				4.40					4.40	40	1		0	0.0	0	0.0
14	Fuel cell input anode				0.15	2.96				3.10	40	10		99	0.0	0	99.0
15	Fuel cell input cathode		46.99	154.74	9.91					211.63	80	1		0	8.5	2	2.5
16	Fuel cell exhaust products		23.49	154.74	26.45	0.00	0.00	0.00	0.00	204.69	80	1		0	17	5	4.9
17	Fuel cell electricity													0		0	55.0
q1	SMR combustor stack heat										117			0	6	2	1.9
q2	SMR product gas heat										250			0	75	22	21.9
q3	3-stage hydrogen compressor heat rejection										40			0	27	8	8.0
q4	Fuel cell heat rejection loop										80			0	124	36	36.3

Configuration 2 — Detailed Process Flow Table— Ambient Pressure SMR, Direct H₂ Fuel Cell

Design Basis		Inputs
Purified hydrogen from PSA	kg/hr	2.96
Fuel cell electricity out	kWe	55
Reference Temperature	Deg. C	40

Process Streams		Mass Flow, kg/hr								T °C	P Atm	HV Btu/lb	kW	Sen Heat kBtu/h	kW	Total kW
		CH ₄	O ₂	N ₂	H ₂ O	H ₂	CO ₂	CO	UHC							
1	Reformer feed natural gas	8.71		0.26			0.18		0.26	9.39	25	1.5	-21537	131	0	130.6
2	Reformer feed water/steam				24.44					24.44	25	1		0	0	0.0
	Feedstock preheat												131	151.7	42	172.7
3	Combustion air for reformer		13.76	45.29						59.05	200	1		0	9.1	2.5
	Reformer product gas (hot)			0.26	10.37	3.71	10.02	8.82	0.66	33.84	800	1	-7216	158	75	178.4
	HTS out			0.26	6.14	4.19	20.35	2.24	0.66	33.84	400	1	-7093	155	36	165.0
	LTS out			0.26	5.78	4.23	21.23	1.68	0.66	33.84	250	1	-7083	155	21	160.6
4	SMR Out (Heat removed from LTS out for preheat)												0		0	0.0
5	SMR product gas (cold) to PSA purifier			0.26	1.38	4.23	21.23	1.68	0.66	29.44	40	10	-8142	155	0	154.7
6	PSA purifier product hydrogen to compressor				1.10	2.96				4.06	40	10	-37593	99	0	98.5
7	Compressed hydrogen to storage					2.96				2.96	30	245	-51605	99	0	98.5
8	PSA purifier product hydrogen to fuel cell					2.96				2.96	40	10	-51605	99	0	98.5
9	PSA residue gas as fuel to SMR combustor			0.26	0.28	1.27	21.23	1.68	0.66	25.38	200	10	-3429	56	6.3	57.9
10	SMR combustor product gas (hot, before preheating feedstock)			45.55	13.18	0.00	25.70	0.00	0.00	84.43		1		0	192	56.2
11	SMR combustor exhaust gas (stack)			45.55	13.18	0.00	25.70	0.00	0.00	84.43	113	1		0	6	1.8
13	SMR product gas knock-out water				4.40					4.40	40	1		0	0.0	0.0
14	Fuel cell input anode				0.15	2.96				3.10	40	10		99	0.0	99.0
15	Fuel cell input cathode		46.99	154.74	9.91					211.63	80	1		0	8.5	2.4
16	Fuel cell exhaust products		23.49	154.74	26.45	0.00	0.00	0.00	0.00	204.69	80	1		0	17	4.6
17	Fuel cell electricity													0		55.0
q1	SMR combustor stack heat										113			0	6	1.8
q2	SMR product gas heat										250			0	75	5.9
q3	3-stage hydrogen compressor heat rejection										40			0	27	7.6
q4	Fuel cell heat rejection loop										80			0	133	36.8
	Fuel Cell Heat Losses															0.2

Configuration 3 — Detailed Process Flow Table— High Pressure SMR, Reformate Fuel Cell

Design Basis		Inputs
Reformate Hydrogen Content to Fuel Cell (1.2xAnode SR)	kg/hr	3.56
Fuel cell electricity out	kWe	55
Reference Temperature	Deg. C	40

Process Streams		Mass Flow, kg/hr								T °C	P Atm	HV Btu/lb	kW	Sen Heat kBtu/h	kW	Total kW
		CH ₄	O ₂	N ₂	H ₂ O	H ₂	CO ₂	CO	UHC							
1	Reformer feed natural gas	7.38		0.26			0.15		0.22	8.00	25	1.5	-21537	111	0	111.2
2	Reformer feed water/steam				20.72					20.72	25	1	0	0	0	0.0
3	Combustion air for reformer		8.54	28.11						36.64	200	1	0	0	5.6	1.6
	Reformer product gas (hot)	0.58		0.26	8.18	3.24	8.75	7.71		28.72	800	1	-7431	138	58.1	16
	HTS out	0.58		0.26	4.66	3.64	17.35	2.24		28.72	400	1	-7312	136	27.8	8
	LTS out	0.58		0.26	4.30	3.68	18.23	1.68		28.72	250	1	-7299	135	16.2	5
	PrOx-in	0.58	2.88	9.74	4.30	3.68	18.23	1.68		41.09	250	2	-5103	135	18.7	5
4	PrOx-out (SMR System Reformate out)	0.00	0.00	9.74	5.38	3.56	22.46	0.00		41.14	250	3	-4463	118	18.4	5
5	SMR product gas (cold) to PSA purifier	0.00	0.00	9.74	5.38	3.56	22.46	0.00	0.00	41.14	40	10	-4463	118	0	118.5
6	PSA purifier product hydrogen to compressor				4.31	2.49				6.80	40	10	-18911	83	0	82.9
7	Compressed hydrogen to storage					2.49				2.49	30	245	-51605	83	0	82.9
9	PSA residue gas as fuel to SMR combustor	0.00		9.74	1.08	1.07	22.46	0.00		34.34	200	10	-1604	36	7.2646	2
10	SMR combustor product gas (hot, before preheating feedstock)			37.85	10.68	0.00	22.46	0.00	0.00	70.99		1	0	0	0	36
11	SMR combustor exhaust gas (stack)			37.85	10.68	0.00	22.46	0.00	0.00	70.99	40	1	0	0	0	0.0
13										0.00						
14	Fuel cell input anode	0.00	0.00	9.74	5.38	3.56	22.46	0.00	0.00	41.14	80	10	-4463	118	3.5	119.5
15	Fuel cell input cathode		46.99	154.74	9.91					211.63	80	1	0	0	8.5	2.4
16	Fuel cell exhaust products		23.49	154.74	26.45	0.59	22.46	0.00	0.00	227.74	80	1	-135	20	19	25.0
17	Fuel cell electricity														0	55.0
q1	SMR combustor stack heat										40			0	0	0.0
q2	SMR product gas heat										250			0	58	4.5
q3	3-stage hydrogen compressor heat rejection										40			0	27	7.6
q4	Fuel cell heat rejection loop										80			0	130	36.2
	Fuel Cell Heat Losses															0.9

Configuration 4 — Detailed Process Flow Table — ATR, Reformate Fuel Cell

SMR PROX System

Design Basis		Inputs
Reformate Hydrogen Content to Fuel Cell (1.2X)	kg/h	3.56
Fuel cell electricity out	kWe	55
Reference Temperature	Deg. C	40

Process Streams		Mass Flow, kg/h								Ti °C	P Atm	HV Btu/lb	kW	Sen Heat kBtu	KW	Total kW
		CH ₄	O ₂	N ₂	H ₂ O	H ₂		CO	UHC	Total						
1	ATR natural gas	11.31		0.33			0.23		0.33	12.20	25	1.5	-20546	162		162.0
2	ATR feed water				9.78					9.78	25	10	0	0		0.0
3	Air for ATR		13.99	46.06						60.05	25	10	0	0		0.0
-	ATR product gas	0.68		46.40	13.15	2.30	1.31	17.87	0.33	82.04	800	10	-2658	141	96.3	169.0
	HTS product gas	0.68		46.40	3.09	3.42	25.87	2.24	0.33	82.04	400		-2538	134	47.2	148.3
-	LTS product gas	0.68		46.40	1.74	3.58	29.17	0.14	0.33	82.04	250	10	-2522	134	27.7	141.7
5	PrOx in (air added)	0.68	3.03	56.37	1.74	3.58	29.17	0.14	0.33	95.03	250	10	-2177	134	33.9	143.6
6	PROX out	0.00		56.37	3.36	3.56	31.26	0.00	0.33	94.88	250	10	-2015	123	30.4	132.4
13	ATR product gas knock-out water				9.79					9.79	40	1	0	0	0.0	0.0
14	Fuel cell input anode (reformat product)			56.37	3.36	3.56	31.26		0.33	94.87	40	1	-2015	123	0.0	123.5
15	Fuel cell input cathode		46.99	154.74	9.91					211.63	80	1	0	0	8.8	2.6
16	Fuel cell exhaust products		23.49	154.74	26.45	0.60	0.00	0.00	0.00	205.29	80	1	-151	20	9.5	22.8
17	Fuel cell electricity															55.0
q1																
q2	ATR product gas heat										800				134.1	39.29
q4	Fuel cell heat rejection loop										80				130.8	38.3
q5	Fuel cell exhaust product heat										80					0.0

Configuration 5 — Detailed Process Flow Table — ATR, Direct H₂ Fuel Cell

SMR PROX System

Design Basis		Inputs
Purified hydrogen from PSA	kg/h	2.96
Fuel cell electricity out	kWe	55
Reference Temperature	Deg. C	40

Process Streams		Mass Flow, kg/h								TI °C	P Atm	HV Btu/lb	kW	Sen Heat kBtu	KW	Total kW
		CH ₄	O ₂	N ₂	H ₂ O	H ₂	CO ₂	CO	UHC							
1	ATR natural gas	13.40		0.39			0.27		0.39	14.45	25	1.5	-20546	192	0.0	191.84
2	ATR feed water				11.58					11.58	25	10	0	0	0.0	0.00
3	Air for ATR		16.57	54.56						71.12	25	10	0	0	0.0	0.00
-	ATR product gas	0.80		54.95	15.57	2.72	1.56	21.17	0.39	97.16	800	10	-2658	167	113.7	200.11
	HTS product gas	0.80		54.95	3.40	4.08	31.29	2.24	0.39	97.17	400		-2535	159	55.8	175.48
-	LTS product gas	0.80		54.95	2.05	4.24	34.59	0.14	0.39	97.17	250	10	-2522	158	32.7	167.85
5	PrOx in (air added)	0.80	3.53	66.57	2.05	4.24	34.59	0.14	0.39	112.31	250	10	-2182	158	39.9	169.95
6	PROX out	0.00		66.57	3.94	4.23	37.02	0.00	0.39	112.15	250	10	-2020	146	35.9	156.86
4	Air Input for PSA Residue combustion		11.62	43.73						55.35	25	1	0	0	-0.9	-0.25
7	PSA purifier product hydrogen to compressor				3.15	2.96				6.11	40	10	-24981	99	0.0	98.61
8	Compressed hydrogen to storage					2.96				2.96	40	245	-51605	99	0.0	98.61
9	PSA purified hydrogen to fuel cell					2.96				2.96	40	10	-51605	99	0.0	98.61
10	PSA residue gas	0.00		66.57	0.79	1.27	37.02	0.00	0.39	106.03	40	10	-697	48	0.0	47.74
															-0.1	-0.03
															-0.1	-0.03
13	ATR product gas knock-out water				11.63					11.63	40	1	0	0	0.0	0.00
14	Fuel cell input anode				0.15	2.96				3.10	40	1	-49189	99	0.0	98.61
15	Fuel cell input cathode		46.99	154.74	9.91					211.63	80	1	0	0	8.8	2.57
16	Fuel cell exhaust products		23.49	154.74	26.45	0.00	0.00	0.00	0.00	204.69	80	1	0	0	16.6	4.87
17	Fuel cell electricity															55.0
q2	ATR product gas heat										800				35.9	10.51
q3	3-stage hydrogen compressor heat rejection										80				27.3	8.00
q4	Fuel cell heat rejection loop										80				123.7	36.26
q5	Fuel cell exhaust product heat										80					0.00

Appendix B. Incremental Emissions for Various Energy Station Operational Scenarios and System Configurations

Table B-1 summarizes the incremental emission analysis results for the representative energy station operational scenarios and system configurations. These results are for a 50 kWe capacity reformer/fuel cell system. See Table 2-2 for the definition of Operational Scenarios and System Configurations. See Section 2.3 for description of incremental emission analysis methodology.

Table B-1. Summary of Incremental Emissions for Representative Energy Station Operational Scenarios and System Configurations

Scenario	Veh/day	System Config	Net Emissions, TPY				
			NOx	CO	UHC	PM	GHG
1	3	1	-0.14	-0.31	-0.94	-0.018	-265.52
1	3	2	-0.09	-0.23	-0.56	-0.011	-160.08
1	3	3	-0.13	-0.28	-0.87	-0.017	-242.26
1	3	4	-0.20	-0.38	-2.12	-0.029	-324.49
1	3	5	-0.10	-0.25	-1.43	-0.015	-90.17
1	7	1	-0.11	-0.23	-0.79	-0.015	-221.63
1	7	2	-0.06	-0.15	-0.40	-0.008	-112.65
1	7	3	-0.10	-0.20	-0.70	-0.013	-195.14
1	7	4	-0.17	-0.30	-1.67	-0.024	-301.75
1	7	5	-0.07	-0.17	-0.98	-0.011	-83.19
1	13	1	-0.07	-0.11	-0.57	-0.010	-155.79
1	13	2	-0.03	-0.05	-0.22	-0.004	-61.20
1	13	3	-0.07	-0.10	-0.52	-0.009	-142.73
1	13	4	-0.14	-0.20	-1.05	-0.018	-280.73
1	13	5	-0.04	-0.07	-0.37	-0.006	-91.83
2	3	1	-0.13	-0.29	-0.90	-0.017	-253.08
2	3	2	-0.09	-0.22	-0.57	-0.011	-160.31
2	3	3	-0.12	-0.26	-0.80	-0.016	-223.56
2	3	4	-0.19	-0.36	-2.00	-0.028	-314.24
2	3	5	-0.10	-0.24	-1.36	-0.015	-96.84
2	7	1	-0.11	-0.23	-0.79	-0.015	-221.63
2	7	2	-0.06	-0.15	-0.39	-0.008	-111.52
2	7	3	-0.09	-0.20	-0.59	-0.011	-169.35
2	7	4	-0.17	-0.30	-1.67	-0.024	-300.75
2	7	5	-0.07	-0.17	-0.98	-0.011	-82.14
2	13	1	-0.07	-0.11	-0.56	-0.010	-155.32
2	13	2	-0.02	-0.03	-0.16	-0.003	-44.88
2	13	3	-0.05	-0.09	-0.36	-0.006	-102.99
2	13	4	-0.13	-0.19	-1.01	-0.018	-271.03
2	13	5	-0.04	-0.06	-0.31	-0.005	-76.08
3	3	1	-0.07	-0.14	-0.48	-0.009	-133.74
3	3	2	-0.04	-0.10	-0.26	-0.005	-74.06
3	3	3	-0.06	-0.13	-0.37	-0.007	-106.31
3	3	4	-0.10	-0.19	-1.04	-0.015	-174.31
3	3	5	-0.05	-0.11	-0.65	-0.007	-48.28
3	7	1	-0.09	-0.18	-0.64	-0.012	-179.11
3	7	2	-0.05	-0.11	-0.30	-0.006	-86.13
3	7	3	-0.07	-0.16	-0.48	-0.009	-135.83
3	7	4	-0.14	-0.24	-1.32	-0.020	-256.33
3	7	5	-0.06	-0.13	-0.74	-0.009	-70.73
3	13	1	-0.07	-0.11	-0.56	-0.010	-155.67
3	13	2	-0.02	-0.04	-0.16	-0.003	-45.23
3	13	3	-0.06	-0.09	-0.36	-0.006	-103.32
3	13	4	-0.13	-0.19	-1.02	-0.018	-271.31
3	13	5	-0.04	-0.06	-0.31	-0.005	-76.33
4	3	1	-0.08	-0.16	-0.52	-0.010	-147.16
4	3	2	-0.05	-0.12	-0.30	-0.006	-84.31
4	3	3	-0.06	-0.15	-0.42	-0.008	-118.66
4	3	4	-0.11	-0.21	-1.15	-0.016	-190.29
4	3	5	-0.05	-0.13	-0.73	-0.008	-54.44
4	7	1	-0.10	-0.19	-0.69	-0.013	-192.80
4	7	2	-0.05	-0.13	-0.34	-0.007	-96.75
4	7	3	-0.08	-0.17	-0.52	-0.010	-148.54
4	7	4	-0.15	-0.26	-1.44	-0.022	-271.19
4	7	5	-0.06	-0.14	-0.82	-0.009	-77.26
4	13	1	-0.07	-0.11	-0.57	-0.010	-155.87
4	13	2	-0.02	-0.04	-0.16	-0.003	-45.43
4	13	3	-0.06	-0.09	-0.36	-0.006	-103.51
4	13	4	-0.13	-0.19	-1.02	-0.018	-271.51
4	13	5	-0.04	-0.06	-0.32	-0.005	-76.72

The incremental emissions shown in Table B-1 were estimated using the methodology described in Section 2.3, the system configuration power analyses described in Section 2.2 and Appendix A, and the emission factors shown in Table B-2. As indicated in Section 2.3, these emission factors were developed using industry standards for boilers and power plant emissions, TIAx emission estimates for reformer systems, and adjusted GREET1.6 results for natural gas fuel cycle emissions. These emission factors were assumed applicable for all operational loads. Simplifying assumptions used in the incremental emissions analysis are given in Table B-3.

Table B-2. Emission Factors for System Components

System Component	NO _x g/kWh	CO g/kWh	UHC g/kWh	PM g/kWh	CO ₂ g/kWh	Fuel Displaced
SMR	0.075	0.023	0.858	0.015	199	NatGas
ATR	0.069	0.023	0.012	0.012	280	NatGas
Fuel Cell	0.146	0.312	1.669	0.035	372	Electricity
Cogen	0.340	0.490	2.601	0.047	662	NatGas
Parasitics	0.146	0.312	1.669	0.035	372	Electricity

Table B-3. Assumptions Used for the Incremental Emissions Calculation

Simplifying Assumptions Used
Parasitic loads scale with reformer load. For example, if the reformer is operating at 50% full capacity, each parasitic component also operates at 50% of its respective full capacity.
The fueling-only station was assumed to have the same size reformer and parasitic loads as the energy station, but no fuel cell power production or cogeneration. The fueling-only station was assumed to operate its reformer at the minimum load required to satisfy the daily hydrogen fueling demand.
The emission results from GREET1.6 were for natural gas extraction through production. In order to capture the post-production fuel cycle-related emissions, the GREET1.6 results were increased by 7%, to account for additional transmission and (i.e., pumping, leakage) losses to the point-of-use.
The greenhouse gas emissions were calculated on a CO ₂ -equivalent basis. We assumed that the UHC emissions were primarily methane, or species with the same specific GHG activity as methane. Thus, the GHG emissions were calculated by added CO ₂ emissions to UHC emissions, with the appropriate weighting for methane: 21 g CO ₂ -equivalent/g methane.
For the power capacity comparison in Figure 2-11, we linearly scaled the power capacity results in Appendix A for each of the cases (i.e., 50kWe, 75kWe, and 100kWe fuel cell/reformer capacity). That figure was based on Operational Scenario 1, so we assumed that the reformer always operated at its full capacity, and the fuel cell used the extra hydrogen produced by the reformer. We also assumed that the trends for avoided NO _x emissions between power capacities were similar to those for other emission species, and thus only showed the results for NO _x .

Figures B-1 through B-5 show the calculation tables used to determine the emissions avoided under operational scenario 1, with 3 vehicles/day, for each of the system configurations. The columns with the units “on/off”—such as the second column from the left labeled “Reformer”—allow the user to include or exclude certain system components from the emissions calculation, by entering a “1” or “0”, respectively. The same calculation tables were used for the fueling-only stations, except that the fuel cell and cogeneration-related columns were changed to “off”, and the reformer was operated at the minimum load required to support the daily vehicle throughput at an average 5 kg per fill.

Time, hr of day	Reformer	FC	Vehicle Fueling	Reformer	FC	Vehicle Fueling Demand	Reformer Cogen	FC Cogen	Feedstock water compressor	Feedstock NG compressor	Combustion air blower	Reformate compressor (to PSA), 10 atm	Reformate compressor (to fuel cell), 2-3 atm	PSA System	High Pressure Compr. Storage	Misc	Emissions					
	Rated kW			124	50		22	41	3	2.5	0.8			1	11	0.5	NOx	CO	UHC	PM	CO2	GHG
hr	on/off	on/off	on/off	kW	kW	kW	on/off	on/off	on/off								grams					
0	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
1	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
2	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
3	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
4	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
5	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
6	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
7	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
8	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
9	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
10	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
11	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
12	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
13	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
14	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
15	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
16	1	1	0	124	50	0	1	1	1	1	1	0	0	1	1	1	-16.7	-37.8	-109	-2.13	-28607	-30906
17	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
18	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
19	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
20	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
21	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
22	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
23	1	1	1	124	32	18	1	1	1	1	1	0	0	1	1	1	-9.06	-24.9	-41.1	-0.81	-12144	-13006
																	-286	-713	-1601	-31.3	-4E+05	-473254

Figure B-1. Configuration 1 — High Pressure SMR, Direct H₂ Fuel Cell

Time, hr of day	Reformer	FC	Vehicle Fueling	Reformer	FC	Vehicle Fueling Demand	Reformer Cogen	FC Cogen	Feedstock water compressor	Feedstock NG compressor	Combustion air blower	Reformate compressor (to PSA); 10 atm	Reformate compressor (to fuel cell); 2-3 atm	PSA System	High Pressure Compr. Storage	Misc	Emissions					
Rated kW				124	50		6	41			0.8	2.5	1	1	11	0.5	NOx	CO	UHC	PM	CO2	GHG
hr	on/off	on/off	on/off	kW	kW	kW	on/off	on/off			on/off						grams					
0	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
1	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
2	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
3	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
4	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
5	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
6	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
7	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
8	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
9	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
10	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
11	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
12	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
13	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
14	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
15	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
16	1	1	0	124	50	0	1	1	0	0	1	1	1	1	1	1	-11.6	-30.5	-71.2	-1.46	-18767	-20262
17	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
18	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
19	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
20	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
21	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
22	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
23	1	1	1	124	32	18	1	1	0	0	1	1	1	1	1	1	-3.91	-17.7	-2.79	-0.13	-2304	-2362.7
																	-163	-540	-683	-15.1	-2E+05	-217803

Figure B-2. Configuration 2 — Ambient Pressure SMR, Direct H₂ Fuel Cell

Time, hr of day	Reformer	FC	Vehicle Fueling	Reformer	FC	Vehicle Fueling Demand	Reformer Cogen	FC Cogen	Feedstock water compressor	Feedstock NG compressor	Combustion air blower	Reformate compressor (to PSA); 10 atm	Reformate compressor (to fuel cell); 2-3 atm	PSA System	High Pressure Compr. Storage	Misc	Emissions					
	Rated kW			108	50		18	36			0.8	2.5	1	1	11	0.5	NOx	CO	UHC	PM	CO ₂	GHG
hr	on/off	on/off	on/off	kW	kW	kW	on/off	on/off			on/off						grams					
0	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
1	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
2	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
3	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
4	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
5	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
6	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
7	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
8	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
9	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
10	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
11	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
12	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
13	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
14	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
15	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
16	1	1	0	0	108	50	0	1	1	0	0	1	1	1	1	1	-15.1	-34.3	-103	-2.03	-26582	-28748
17	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
18	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
19	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
20	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
21	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
22	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
23	1	1	1	1	108	32	18	1	1	0	0	1	1	1	1	1	-8.1	-22.4	-39.4	-0.79	-11310	-12138
																	-258	-645	-1520	-30.1	-4E+05	-440799

Figure B-3. Configuration 3 — High Pressure SMR, Reformate Fuel Cell

Time, hr of day	Reformer	FC	Vehicle Fueling	Reformer	FC	Vehicle Fueling Demand	Reformer Cogen	FC Cogen	Feedstock water compressor	Feedstock NG compressor	Combustion air blower	Reformate compressor (to PSA); 10 atm	Reformate compressor (to fuel cell); 2-3 atm	PSA System	High Pressure Compr. Storage	Misc	Emissions					
	Rated kW			119	50		39	38			0.8	2.5	1	1	11	0.5	NOx	CO	UHC	PM	CO ₂	GHG
hr	on/off	on/off	on/off	kW	kW	kW	on/off	on/off			on/off						grams					
0	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
1	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
2	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
3	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
4	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
5	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
6	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
7	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
8	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
9	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
10	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
11	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
12	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
13	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
14	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
15	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
16	1	1	0	119	50	0	1	1	0	0	1	1	1	1	1	1	-22.9	-45.4	-254	-3.37	-30030	-35370
17	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
18	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
19	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
20	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
21	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
22	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
23	1	1	1	119	32	18	1	1	0	0	1	1	1	1	1	1	-15.6	-33	-189	-2.1	-14282	-18244
																	-439	-904	-5118	-61.8	-5E+05	-591990

Figure B-4. Configuration 4 — ATR, Reformate Fuel Cell

Time, hr of day	Reformer	FC	Vehicle Fueling	Reformer	FC	Vehicle Fueling Demand	Reformer Cogen	FC Cogen	Feedstock water compressor	Feedstock NG compressor	Combustion air blower	Reformate compressor (to PSA); 10 atm	Reformate compressor (to fuel cell); 2-3 atm	PSA System	High Pressure Compr. Storage	Misc	Emissions					
	Rated kW			141	50		11	39			0.8	2.5	1	1	11	0.5	NOx	CO	UHC	PM	CO2	GHG
hr	on/off	on/off	on/off	kW	kW	kW	on/off	on/off			on/off						grams					
0	1	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
1	1	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
2	1	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
3	1	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
4	1	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
5	1	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
6	1	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
7	1	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
8	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
9	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
10	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
11	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
12	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
13	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
14	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
15	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
16	1	1	0	141	50	0	1	1	0	0	1	1	1	1	1	1	-12.1	-31.6	-184	-1.86	-6020	-9879.8
17	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
18	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
19	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
20	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
21	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
22	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
23	1	1	1	141	32	18	1	1	0	0	1	1	1	1	1	1	-4.75	-19.1	-117	-0.57	9966.5	7504.3
																	-181	-572	-3413	-25.2	95316	23646

Figure B-5. Configuration 5 — ATR, Direct H₂ Fuel Cell

Using the incremental energy consumption projections for each of the system configurations and operational scenarios considered, and the commercial electricity and natural gas rates shown in Table B-4, we calculated the corresponding annual incremental cost of purchasing utility electricity and natural gas for an energy station. For example, the hourly reformer power and fuel cell power values shown in Figure B-1 were used to project the annual incremental energy cost for operational scenario #1, system configuration #1 with 3 vehicles/day. Assuming station operation 365 days/year at the projected levels, the resulting cost (savings) due to incremental energy use were determined as shown in Table B-5. The energy rates in Table B-4 were based on forecasted values for each year between 2004 and 2013.

Table B-4. Price Projections for Electricity and Natural Gas Prices

	2004	2007	2010	2013
Electricity (\$/kWh) ^a	12.8	12.6	12.3	12.2
Natural Gas (\$/MMBtu) ^b	7.8	7.1	6.8	7.3

^a Taken from California Energy Commission forecast for CA state-wide average retail electricity prices

^b Projection of national average price for commercial natural gas using U.S. Energy Information Administration data

Table B-5. Added Annual Expense for Given System Configurations and Operational Scenarios

Scenario	Veh/day	Reformer	Added Expense of Utility Power (nominal \$/yr)									
			2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
1	3	1	(27,042)	(26,542)	(26,545)	(26,579)	(25,989)	(25,971)	(26,020)	(25,855)	(25,481)	(25,737)
1	3	2	(29,614)	(29,068)	(29,071)	(29,110)	(28,463)	(28,443)	(28,497)	(28,316)	(27,906)	(28,186)
1	3	3	(31,837)	(31,247)	(31,250)	(31,290)	(30,596)	(30,574)	(30,631)	(30,438)	(29,998)	(30,300)
1	3	4	(28,572)	(28,042)	(28,044)	(28,080)	(27,458)	(27,437)	(27,488)	(27,315)	(26,922)	(27,193)
1	3	5	(29,592)	(29,046)	(29,051)	(29,089)	(28,442)	(28,423)	(28,477)	(28,296)	(27,885)	(28,164)
1	7	1	(16,594)	(16,286)	(16,288)	(16,309)	(15,947)	(15,935)	(15,965)	(15,864)	(15,635)	(15,793)
1	7	2	(18,156)	(17,821)	(17,823)	(17,846)	(17,450)	(17,438)	(17,471)	(17,360)	(17,108)	(17,280)
1	7	3	(19,529)	(19,167)	(19,168)	(19,193)	(18,767)	(18,753)	(18,788)	(18,670)	(18,401)	(18,586)
1	7	4	(17,113)	(16,794)	(16,794)	(16,816)	(16,443)	(16,430)	(16,460)	(16,358)	(16,123)	(16,286)
1	7	5	(18,147)	(17,812)	(17,814)	(17,838)	(17,441)	(17,430)	(17,463)	(17,352)	(17,100)	(17,271)
1	13	1	(922)	(903)	(902)	(903)	(884)	(882)	(883)	(878)	(867)	(877)
1	13	2	(969)	(950)	(950)	(951)	(931)	(930)	(931)	(926)	(913)	(922)
1	13	3	(1,068)	(1,046)	(1,045)	(1,046)	(1,024)	(1,022)	(1,024)	(1,018)	(1,005)	(1,015)
1	13	4	77	78	80	81	78	80	81	79	75	74
1	13	5	(979)	(960)	(960)	(961)	(940)	(939)	(940)	(935)	(922)	(932)
2	3	1	(27,837)	(27,322)	(27,325)	(27,360)	(26,753)	(26,734)	(26,784)	(26,615)	(26,230)	(26,494)
2	3	2	(30,745)	(30,177)	(30,180)	(30,220)	(29,548)	(29,528)	(29,583)	(29,396)	(28,971)	(29,262)
2	3	3	(31,651)	(31,065)	(31,068)	(31,108)	(30,418)	(30,396)	(30,452)	(30,261)	(29,823)	(30,123)
2	3	4	(29,773)	(29,221)	(29,222)	(29,260)	(28,611)	(28,590)	(28,642)	(28,463)	(28,053)	(28,336)
2	3	5	(30,724)	(30,157)	(30,161)	(30,201)	(29,529)	(29,510)	(29,565)	(29,378)	(28,952)	(29,242)
2	7	1	(16,594)	(16,286)	(16,288)	(16,309)	(15,947)	(15,935)	(15,965)	(15,864)	(15,635)	(15,793)
2	7	2	(18,156)	(17,821)	(17,823)	(17,846)	(17,450)	(17,438)	(17,471)	(17,360)	(17,108)	(17,280)
2	7	3	(17,286)	(16,967)	(16,969)	(16,991)	(16,614)	(16,602)	(16,633)	(16,528)	(16,289)	(16,452)
2	7	4	(17,113)	(16,794)	(16,794)	(16,816)	(16,443)	(16,430)	(16,460)	(16,358)	(16,123)	(16,286)
2	7	5	(18,147)	(17,812)	(17,814)	(17,838)	(17,441)	(17,430)	(17,463)	(17,352)	(17,100)	(17,271)
2	13	1	(913)	(894)	(893)	(894)	(875)	(873)	(874)	(870)	(859)	(868)
2	13	2	(960)	(942)	(942)	(943)	(922)	(921)	(923)	(917)	(905)	(914)
2	13	3	1,183	1,162	1,162	1,163	1,137	1,137	1,139	1,132	1,115	1,126
2	13	4	85	87	89	90	86	88	89	87	83	82
2	13	5	(971)	(952)	(952)	(953)	(932)	(931)	(932)	(927)	(914)	(924)
3	3	1	(11,641)	(11,425)	(11,426)	(11,441)	(11,187)	(11,179)	(11,200)	(11,130)	(10,969)	(11,079)
3	3	2	(12,707)	(12,472)	(12,474)	(12,490)	(12,213)	(12,204)	(12,227)	(12,150)	(11,974)	(12,094)
3	3	3	(12,415)	(12,186)	(12,187)	(12,203)	(11,932)	(11,924)	(11,946)	(11,871)	(11,699)	(11,816)
3	3	4	(12,123)	(11,897)	(11,898)	(11,913)	(11,649)	(11,640)	(11,662)	(11,589)	(11,422)	(11,537)
3	3	5	(12,698)	(12,464)	(12,466)	(12,483)	(12,205)	(12,197)	(12,220)	(12,142)	(11,966)	(12,086)
3	7	1	(11,625)	(11,410)	(11,410)	(11,425)	(11,172)	(11,164)	(11,184)	(11,114)	(10,954)	(11,064)
3	7	2	(12,666)	(12,432)	(12,434)	(12,450)	(12,174)	(12,165)	(12,188)	(12,111)	(11,935)	(12,055)
3	7	3	(11,710)	(11,494)	(11,495)	(11,510)	(11,255)	(11,247)	(11,268)	(11,197)	(11,035)	(11,145)
3	7	4	(12,007)	(11,783)	(11,783)	(11,797)	(11,537)	(11,527)	(11,548)	(11,476)	(11,312)	(11,427)
3	7	5	(12,662)	(12,428)	(12,430)	(12,446)	(12,169)	(12,161)	(12,184)	(12,107)	(11,931)	(12,051)
3	13	1	(923)	(904)	(903)	(904)	(885)	(883)	(884)	(879)	(868)	(878)
3	13	2	(973)	(954)	(954)	(955)	(934)	(933)	(935)	(929)	(916)	(925)
3	13	3	1,169	1,147	1,148	1,149	1,124	1,123	1,125	1,118	1,102	1,113
3	13	4	73	75	77	77	74	76	77	75	71	71
3	13	5	(983)	(964)	(964)	(965)	(944)	(942)	(944)	(938)	(926)	(935)
4	3	1	(13,209)	(12,965)	(12,966)	(12,983)	(12,695)	(12,686)	(12,709)	(12,629)	(12,447)	(12,572)
4	3	2	(14,518)	(14,250)	(14,252)	(14,271)	(13,954)	(13,944)	(13,971)	(13,882)	(13,681)	(13,818)
4	3	3	(14,252)	(13,988)	(13,990)	(14,008)	(13,697)	(13,687)	(13,713)	(13,626)	(13,429)	(13,564)
4	3	4	(13,893)	(13,635)	(13,635)	(13,653)	(13,350)	(13,340)	(13,365)	(13,281)	(13,090)	(13,222)
4	3	5	(14,509)	(14,241)	(14,243)	(14,262)	(13,945)	(13,936)	(13,962)	(13,873)	(13,672)	(13,809)
4	7	1	(13,225)	(12,979)	(12,980)	(12,997)	(12,709)	(12,699)	(12,723)	(12,643)	(12,461)	(12,586)
4	7	2	(14,523)	(14,254)	(14,256)	(14,275)	(13,958)	(13,948)	(13,974)	(13,886)	(13,685)	(13,822)
4	7	3	(13,591)	(13,340)	(13,342)	(13,359)	(13,082)	(13,053)	(13,078)	(12,995)	(12,807)	(12,936)
4	7	4	(13,583)	(13,330)	(13,330)	(13,347)	(13,052)	(13,041)	(13,065)	(12,984)	(12,798)	(12,927)
4	7	5	(14,517)	(14,249)	(14,250)	(14,269)	(13,952)	(13,943)	(13,969)	(13,880)	(13,679)	(13,816)
4	13	1	(946)	(927)	(926)	(927)	(907)	(905)	(906)	(902)	(890)	(900)
4	13	2	(996)	(977)	(977)	(978)	(957)	(956)	(957)	(951)	(938)	(948)
4	13	3	1,146	1,124	1,125	1,126	1,101	1,100	1,102	1,095	1,080	1,090
4	13	4	50	52	54	54	52	54	55	53	49	48
4	13	5	(1,066)	(987)	(987)	(988)	(966)	(965)	(966)	(961)	(948)	(958)

Appendix C - Energy Station Site Visit Questionnaire

Location: Port Hueneme

Date Visited: October 16, 2003

Present: Robb Barnitt, Jon Leonard (TIAX)

Dave Cook, Allen Miller, Bob, Vern (Naval Facilities Engineering Service Center)

1. Where would the proposed Reformer/Fuel Cell/Hydrogen Fueling Station be located? (note indoor/outdoor and dimensions of space)

- Port Hueneme Pool: Slated for 60 kW Capstone microturbine
- Point Mugu Pool: Adjacent (~300') to housing
- Large laundry facility on base
- Gym and showers adjacent to pool
- Building 1100: Large building, cooling load year round, high profile, hub for engineering department
- Building 1000: Across the street from Bldg 1100
- Building 850: Has 25 kW rooftop PV installation; on sunny days exceeds building load. A city block from Building 1100. Tour destination for public (?) and high brass.

2. Natural Gas Supply Information

a. Gas company

- SoCal Gas

b. Current consumption and rate schedule

- Specifics unknown at time of meeting – Base-wide demand is large

c. Supply pressure

- 10-12 psi in the past. High pressure line for CNG station is ~100 psi

d. Distance to proposed reformer location

- Close to Bldg 850 (see AutoCAD drawings)

3. Water Supply

a. Water company

- City of Port Hueneme Water District

b. Current consumption and rate schedule

- \$2 per thousand gallons

c. Supply pressure

- New water lines installed recently on base. Assume 35-100 psi.

d. Distance to proposed reformer location

- Unknown

4. Alternative Fuel Vehicles

a. Current alt fuel fleet (number of vehicles, fuels, range, typical miles/day, fueling schedules)

- Navy relies on flex fuel vehicles and biodiesel credits.
- Charging stations either removed or disconnected.
- Evs gone
- GSA took over procurement of fleet in order to obtain average fleet age of 6 years (from 10 years)
- NGVs > 200 at one time, but very few left

b. Expected future hydrogen fuel cell vehicles (number, expected mileage)

- None to date, but very interested.
- Positive outlook on attempting to demonstrate

5. Existing Electrical Information

a. Electric Company

- SoCal Edison

b. Currently sell to grid? In the past?

- Building 850 net metering. Occasional sell back, but overall the base is a consumer.

c. Current consumption profile (kWh per hour, weekday, weekend, month, year)

- Building 1100 – 200 kW is a rough guess
- On the order of 50 million kWh/yr per base

d. Electricity Tariff/Rate schedule

- 11.5 cents/kWh on the average. Peak penalty in the summer. Not sure of peak cost.

e. Location of electrical box relative to proposed FC location

- Options abound. May not be most conveniently located FC footprint.

f. Phase, voltage, amperage

- Unknown

6. Existing Hot Water/Steam Use

Navy is phasing out steam, and trending toward hot water.

a. What is hot water/steam used for?

- 2 pools
- laundry
- Several gyms with showers
- All of the above are approx. 0.5 miles from Building 850
- Potential biodiesel production facility to be installed

b. Boiler/heater size in MMBtu/hr

- Unknown

c. Steam/water flowrate

- Unknown

d. Steam/water output and input temperatures

- Unknown

e. Fuel used

- Unknown

f. Demand Profile (day/night, weekday/weekend, summer/winter)

- Unknown
- g. Location relative to proposed FC location
- Unknown

Photo	Description
Proposed location of biodiesel production facility. Footprint predicted to be ~ 10' x 20'. Distance to Building 850 is approximately 300 yards.
Vehicle parking. Disconnected EV charging station. Approximately 100 yards from Bldg 850.

Front of Bldg 850. PV array on roof (not operational at this time, but due to be repaired)

Front of Bldg 850, EV charging stations (disconnected).

Rear of Bldg 850, potential area for FC/Reformer Unit. PV array on main roof to right, as well as garage roof on left. PV inverter and other hardware stored in garage behind white roller door.

Rear of Bldg 850 again.

Fueling facility, including one CNG dispenser. Located approximately 200 yards from Bldg 850.