STATE OF CALIFORNIA ENERGY COMMISSION

Arnold Schwarzenegger
Governor

OPTIMIZATION OF NOVEL DISTRIBUTED ENERGY NETWORKS TO REDUCE GREENHOUSE GAS EMISSIONS IN CALIFORNIA

PIER FINAL DRAFT PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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Renewable Energy Technologies

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Optimization of Novel Distributed Energy Networks to Reduce Greenhouse Gas Emissions in California is the final draft report for the *Optimization of Novel Distributed Energy Networks to Reduce Greenhouse Gas Emissions in California* project (contract number XXX□XX□XXX, work authorization number [insert #] or grant number [insert #] CIEE Contract MR-043?) conducted by Stanford University and the University of California at Berkeley. The information from this project contributes to PIER's Energy□Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916□654□5164.

Table of Contents

List of Figures

List of Tables

Abstract

Stationary combined heat-and-power (CHP) fuel cell systems (FCSs) can provide electricity and heat for buildings, and can reduce greenhouse gas (GHG) emissions significantly if they are configured with an appropriate installation and operating strategy. The Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*) is an optimization tool that was developed and deployed to allow users to evaluate different strategies for installing and operating CHP FCSs in California buildings. The MERESS model examines unique strategies that commercial industry has typically overlooked. It incorporates the pivotal choices that FCS manufacturers, building owners, emission regulators, competing generators, and policy makers make, and empowers them to evaluate the effect of their choices directly. The choice of operating strategy results in trade-offs among three important goals: 1) GHG emission reductions, 2) cost savings to building owners in procuring electricity and heat, and 3) increasing FCS manufacturer sales revenue. The *MERESS* model allows users to evaluate these design trade-offs and to identify the optimal control strategies and building load curves for installation based on either 1) maximum GHG emission reductions or 2) maximum cost savings to building owners.

The *MERESS* model is deployed to show illustrative results for a California campus town. The *MERESS* model is run to evaluate one of the most challenging FCS types to implement for CO_2 reductions, the Phosphoric Acid Fuel Cell (PAFC) system. According to *MERESS*, relative to a base case with no fuel cells installed, this town achieves the highest 1) GHG emission reductions, 2) cost savings to building owners, and 3) FCS manufacturer sales revenue with three different operating strategies, under a scenario of full incentives and a \$100/tonne CO_2 tax (Scenario D). It achieves its maximum carbon dioxide (CO_2) emission reduction, 37% relative to a base case of no FCSs installed, with operating Strategy V: stand alone operation (SA), no load following (NLF), and a fixed heat-to-power ratio (FHP) [SA, NLF, FHP]. The town's building owners gain the highest cost savings, 25%, with Strategy I: electrically and thermally networked (NW), electricity power load following (ELF), and a variable heat-to-power ratio (VHP) [NW, ELF, VHP]. FCS manufacturers have the highest sales revenue with Strategy III: NW, NLF, with a fixed heat-to-power ratio (FHP) [NW, NLF, FHP]. Strategies III and V are partly consistent with the way that FCS manufacturers design their systems today, primarily as NLF with a FHP. By contrast, Strategy I is avant-garde for the fuel cell industry, in particular, in its use of a VHP. Without any state and federal incentives or carbon tax (Scenario A), Strategy I is economical, although marginally so, with 3% cost savings, and a 29% reduction in CO_2 emissions. No particular building type stands out as consistently achieving the highest CO_2 emission reductions or cost savings (Scenarios B and E). However, buildings with load curves similar to Stanford's Mudd Chemistry building (a wet laboratory) achieve maximal cost savings (1.5% with full federal and state incentives but no carbon tax) and maximal CO_2 emission reductions (32%). (Wet laboratories are buildings designed to handle multiple experimental set-ups involving chemicals, drugs, biological matter, and/or electronics, which require specialized piped utilities, direct ventilation, exhaust fume extractors, workbenches designed for noxious fumes, dust control, and/or temperature-and humidity-sensitive heating, ventilating, and air-conditioning (HVAC) systems. They include biology and chemistry labs.)

Keywords: Maximizing Emission Reductions and Economic Savings Simulator (MERESS), fuel cell system (FCS), greenhouse gas emissions (GHG), carbon dioxide (CO_2) emissions, networks, cogeneration, combined heat and power (CHP)

Executive Summary

Introduction

Greenhouse gas (GHG) emissions and energy use could be reduced significantly through the use of stationary fuel cell systems (FCSs). Stationary FCSs are small scale power plants that can provide both electricity and useful heat directly to buildings with low emissions. Currently, U.S. electric power plants waste on average 68% of the available energy in their fuel, and boilers waste an additional 28% on average. These traditionally separate processes of 1) electricity generation and 2) useful heat recovery can be combined in a single process, known as *cogeneration* or *combined-heat and power* (CHP). CHP plants can produce the same quantity of electricity and recoverable heat using less fuel and producing less GHG emissions. Power plants that create electricity close to the buildings they serve are referred to as *distributed* generators. The research presented here delineates the most effective ways to use stationary distributed CHP FCSs to reduce GHG emissions at reasonable cost, through the development and use of an optimization tool called the Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*).

Purpose

The research team expanded the realm of possibilities for FCS installation and control by identifying and examining unique design options, which commercial industry has not typically pursued. FCSs can be installed and controlled using innovative designs, such as

- Stand alone (SA) or networked (NW),
- Heat load following (HLF), electricity load following (ELF), or no load following (NLF), and
- Variable heat-to-power ratio (VHP) or fixed heat-to-power ratio (FHP).

Most prototype FCSs today are installed as SA, NLF, and FHP. By contrast, this analysis enables fuel cell developers and building owners to think outside of this confined box.

The *MERESS* simulation and optimization tool was developed and deployed to allow users to evaluate different strategies for installing and operating distributed CHP FCSs in California buildings. The *MERESS* model allows users to evaluate the electricity and heat supplied by networks of FCSs against real-time electricity and heating demand in California buildings. The *MERESS* model combines 1) engineering data describing the real-world operation of FCSs with 2) dynamic energy demand data from California residences, office buildings, and industrial facilities. The *MERESS* model allows users to evaluate the operation of these systems in different network configurations against the resultant change in GHG. The *MERESS* model allows a user to optimize the network's design either to minimize GHG emissions for electricity and heat provision or to minimize energy costs. A primary goal of the *MERESS* model is to use relatively inexpensive simulation studies to identify more financially and environmentally effective ways to design and install FCS.

Project Objectives

The goal of this project is to develop a simulation tool to evaluate the electricity and heat supplied by networks of FCSs against real-time electricity and heating demand in California buildings. The researchers completed the following tasks:

1) Evaluate GHG emission reductions in five main types of California buildings with the use of FCSs, so as to determine the most suitable building types for implementation.
2) Evaluate GHG emission reductions with different network configurations characteristic for California (stand alone, electrically and thermally networked), so as to determine the most suitable network designs.
3) Identify potential policy options available to California for encouraging the design of distributed energy networks that reduce GHG emissions.

For reference, the five main types of buildings investigated were offices/classrooms, museums/libraries, residences, wet laboratories, and dry laboratories. (Wet laboratories are buildings designed to handle multiple experimental set-ups involving chemicals, drugs, biological matter, and/or electronics, which require specialized piped utilities, direct ventilation, exhaust fume extractors, workbenches designed for noxious fumes, dust control, and/or temperature-and humidity-sensitive heating, ventilating, and air-conditioning (HVAC) systems. They include biology and chemistry labs. By contrast, dry laboratories are buildings that primarily handle materials, electronic equipment, or large instruments that require a dry environment. They may require specialized equipment such as high performance HVAC, exhaust fume extractors, vibration control, and/or dust control. Examples include computing facilities, robotics labs, and clean rooms.)

To provide an even more comprehensive modeling tool and analysis, and to address reviewer suggestions in response to the original proposal, the research team expanded the original Project Objectives to include these goals as well:

4) Analyze GHG reductions in the context of costs,
5) Evaluate a larger array of building types and network configurations, and
6) Develop recommendations not just for policy makers, but also for GHG emission inventory developers, FCS manufacturers, and building owners.

The *MERESS* model was developed and deployed to tests 5 different game-changing installation and operating strategies. The underlying design options behind these strategies are explained in detail in the *Introduction* under the Sub-section 1.5*: Game-Changing Designs for Installing* on page 25. These 5 strategies are tested against a base case in which no FCSs are installed, and heat and power are provided exclusively by a competing generator or set of competing generators defined by the MERESS model's user.

- Base Case: no fuel cells; competing generator defined by user
- Strategy I: NW, ELF, VHP
- Strategy II: NW, HLF, VHP
- Strategy III: NW, NLF, FHP
- Strategy IV: SA, HLF, VHP

- Strategy V: SA, NLF, FHP

These five strategies are unique in that fuel cell manufacturers have not typically designed these features (such as VHP) and these control strategies (such as HLF) into their commercially-available systems. They also typically have not installed systems to be both thermally and electrically NW. Most manufacturers build and install their systems to be SA, NL, with a FHP, or according to Strategy V above. In this way, Strategy V acts as a benchmark of status quo designs against which to compare the performance of other strategies. A primary goal of the *MERESS* model is to use relatively inexpensive simulation studies to identify more financially and environmentally effective ways to design and install FCSs. For this reason, *MERESS* is a system-wide model of an entire energy network composed of FCSs and competing generator(s).

Project Outcomes

Simulation results from various model runs of *MERESS* are highlighted here. For these results presented, the base case competing generator is a high-performance CHP combined cycle natural gas turbine (CCGT) power plant. The *MERESS* model is run to evaluate one of the most challenging FCS types to implement for CO_2 reductions, the Phosphoric Acid Fuel Cell (PAFC) system.

- Scenario A examines the case of no state or federal incentives or a carbon tax. In Scenario A, Strategy I [NW, ELF, VHP] achieves the highest reductions in carbon dioxide (CO_2) emissions, 29% relative to the base case of no FCSs installed, with a marginal energy cost savings of 3% annually. In this scenario, Strategy I also shows the most installations or sales, 17% of the total average electrical power installed in the geographic area. Producers typically associate increasing sales revenue with profit maximization. Figure 1 summarizes these results.

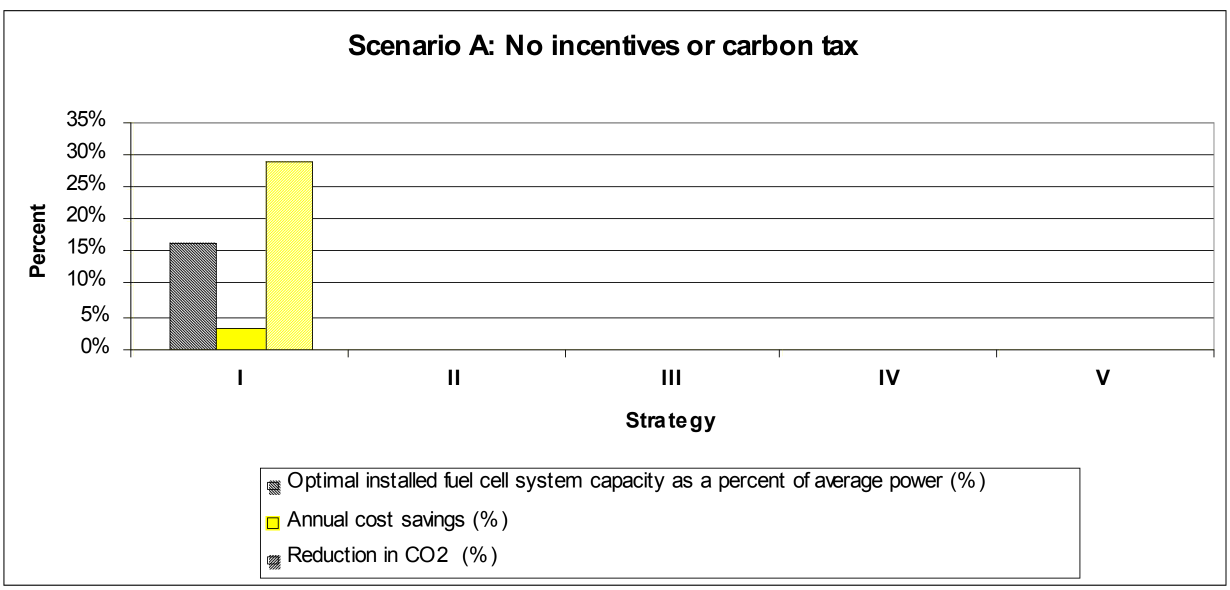


Figure 1: Summary of Scenario A results

- Scenario B examines the case of full state and federal incentives, but no carbon tax. In Scenario B, Strategy I again achieves the highest annual energy cost savings, 15%

relative to the base case, and the highest reduction in CO_2 emissions, 31% relative to the base case. By contrast, Strategy III [NW, NLF, FHP] achieves the highest number of installations, 46% of average electrical power installed. This comparison illustrates a dichotomy between the most economical strategy for building owners and the most economical strategy for fuel cell manufacturers. Under Scenario B, if either Strategies IV or V are implemented, then the most economical installations in both cases are wet laboratory buildings. Wet laboratories are buildings designed to handle multiple experimental set-ups involving chemicals, drugs, biological matter, and/or electronics, which require specialized piped utilities, direct ventilation, exhaust fume extractors, workbenches designed for noxious fumes, dust control, and/or temperature-and humidity-sensitive heating, ventilating, and air-conditioning (HVAC) systems. They include biology and chemistry labs. Figure 2 summarizes these results.

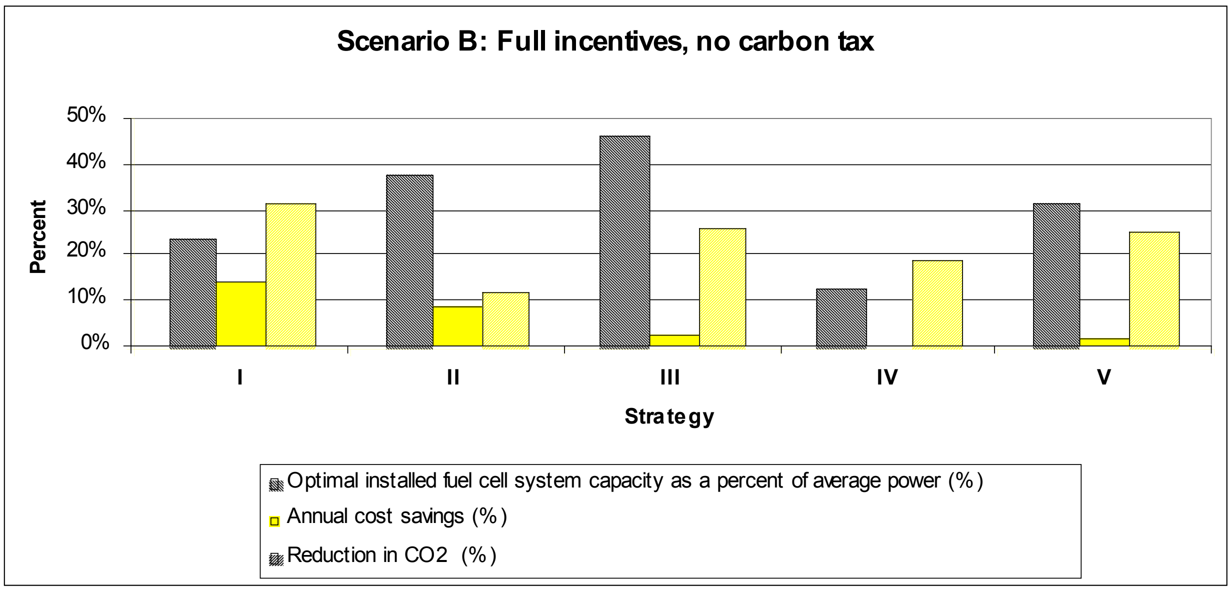


Figure 2: Summary of Scenario B results

- Scenario C examines the case of full state and federal incentives and a \$20/tonne CO_2 tax. In Scenario C, Strategy I again achieves the highest annual energy cost savings, 17% relative to the base case, and the highest reduction in CO_2 emissions, 33% relative to the base case. By contrast, Strategy III again achieves the highest number of installations, 49% of average electrical power installed. Figure 3 summarizes these results.

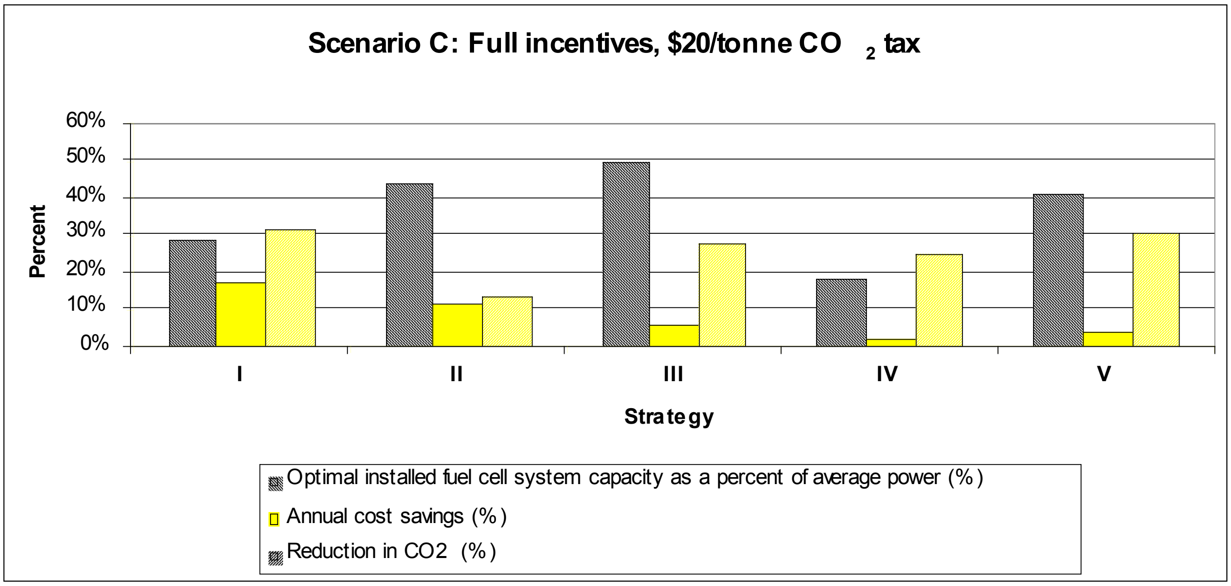


Figure 3: Summary of Scenario C results

- Scenario D examines the case of full state and federal incentives and a $100/tonne CO_2 tax. Scenario D illustrates a scenario in which these three competing goals (cost savings to building owners, GHG emission reductions, and FCS manufacturer sales revenue) are maximized under three different strategies. The highest annual energy cost savings are achieved with Strategy I, with a 25% savings relative to the base case. The highest reduction in CO_2 emissions is with Strategy V [SA, NLF, FHP], yielding a 34% CO_2 reduction relative to the base case. The most economical strategy for building owners is with Strategy III, with 60% of average electrical power covered by FCSs installed. Figure 4 summarizes these results.

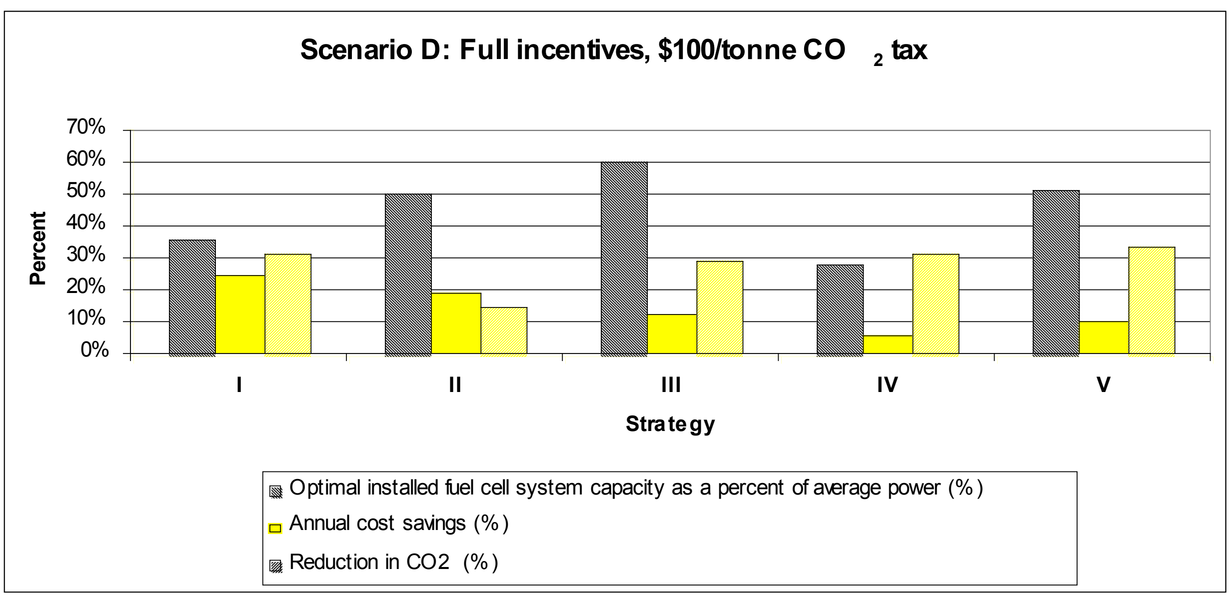


Figure 4: Summary of Scenario D results

- Scenario E examines the case of an unrealistically high carbon tax ($1,000,000/tonne CO_2) so as to alter the function of the model such that the model optimizes not for the highest financial savings, but rather the highest reduction in CO_2 emissions. The results for Scenario E demonstrate that the strategies that achieve the highest reductions in CO_2 emissions are Strategies I, III, and V. Of these, Strategy V achieves the maximum reduction in CO_2 emissions, although Strategies I and III are not far behind. Among Strategies I, III, and V, Strategy III leads to higher sales for FCS manufacturers. Strategy II leads to the absolute highest FCS sales for fuel cell manufacturers, but the lowest absolute CO_2 emission reductions. Figure 5 summarizes these results.

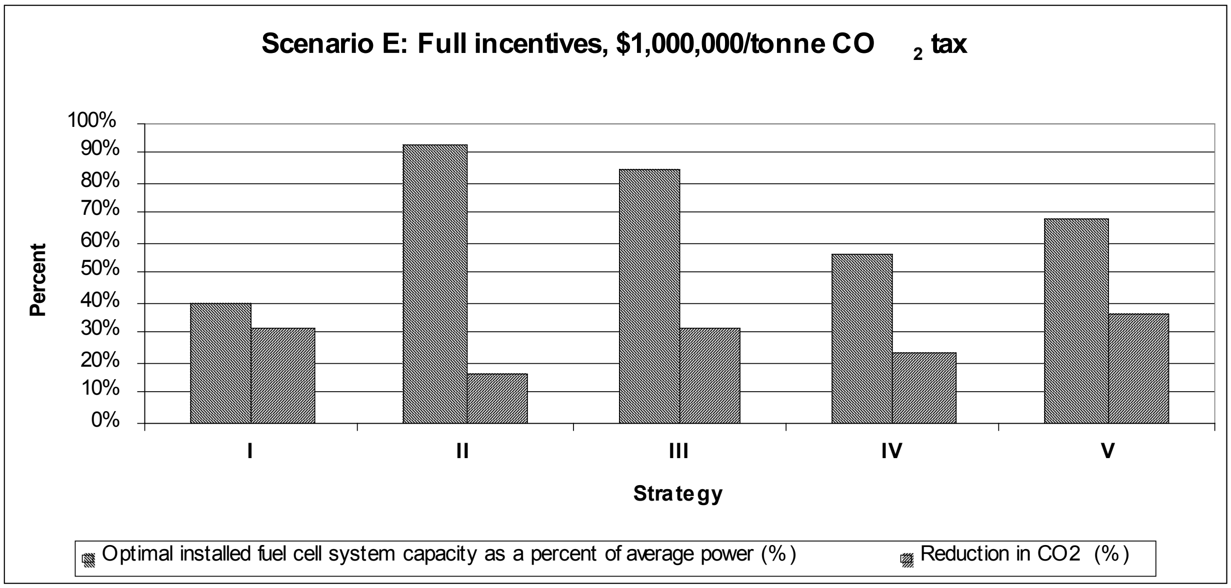


Figure 5: Summary of Scenario E results

Strategies are compared within each scenario. Scenarios are compared in *Section 3.6 Summary Trends Based on Scenarios B, C, and D*, and in Figures 10 and 11.

Conclusions

In evaluating GHG emission reductions with the use of FCSs in California buildings, for the California buildings and town evaluated here, the research team makes several conclusions:

- The electricity and heating load curves of individual buildings are extremely important in determining the economics and GHG emission reduction from an installation.
- These load curves are extremely important because the strategy that achieves the highest reductions in CO_2 emissions is with SA operation, in which one or a few FCSs manipulate their operation to meet the instantaneous electricity and heating demand from these buildings described by their load curves, without additional back-up or buffer of a surrounding electrical or thermal network.

- Specifically, the highest reductions in CO_2 emissions were observed with Strategy V, which incorporates SA operation, HLF, and with a FHP.
- For this stand alone strategy (Strategy V), the best building load curves for maximum CO_2 reductions were identified. The top three of these load curves were those for Stanford's Seeley G. Mudd Chemistry building, the Braun Music building, and the Edward L. Ginzton Labs and Annex.
- No particular building type (such as a wet laboratory or residence) stands out as maximizing any of these three goals consistently, across strategies: GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue.
- This last point above underscores the pivotal role that the *MERESS* model can play in being able to test out a particular building's load curves.

In evaluating GHG emission reductions with the use of FCSs under different network configurations, for the California buildings and town evaluated here, the research team makes several conclusions:

- Under Scenario D, with full government incentives and a \$100/tonne CO_2 tax, three different strategies achieve the highest GHG emission reductions, cost savings to building owners, and FCS manufacturer profitability.
    - Strategy V achieves the highest reductions in CO_2 emissions.
    - Strategy I provides energy for building owners with the lowest total cost, including the fixed and variable costs of resources and fuel over the investment time horizon.
    - Strategy III provides the highest sales revenue for fuel cell manufacturers
- Under Scenario A, without any state and federal incentives or carbon tax, Strategy I is economical, although marginally so. The significance of this finding is to demonstrate that just by changing the installation and operating strategy for FCSs, they can be installed economically, without any governmental incentives. FCSs have not typically been designed and installed to be connected to thermal networks, to follow electrical loads, and to achieve a VHP, either separately or in concert. This combined scenario and strategy demonstrate that FCSs can outperform conventional heat and electricity generation if they are built to provide both electricity and heat through CHP, operate at some fraction of total energy demand in a geographic area, and are connected to a pre-existing thermal network (district heating pipelines).
- The strategies that achieve the highest cost savings for building owners differ greatly from the strategies that achive the highest FCS manufacturer sales revenue.
- Strategies III and V are consistent with the way that FCS manufacturers design their systems today, primarily as NLF with a FHP. Most prototype FCSs today are installed as SA, NLF, and FHP, or according to Strategy V above. In this way, Strategy V acts as a benchmark of status quo designs against which to compare the performance of other strategies.

- By contrast, Strategy I is avant-garde for the fuel cell industry, in particular, in its use of a VHP. These results suggest that fuel cell developers and building owners could benefit by thinking outside of the box.
- In all scenarios evaluated, higher energy cost savings are achieved with linking FCSs together in electrical and thermal networks, as opposed to installing them SA.
- NW, combined with either electrical or thermal load following and VHP, improved economic performance.

Recommendations

In the course of developing these conclusions, the research team identified four key recommendations for policy makers in California for encouraging industry and property owners to implement distributed energy networks that reduce GHG emissions:

- Create incentives for FCS manufacturers to build systems with a VHP
- Create partnerships between FCS makers and energy service companies (ESCO)
- Facilitate installing systems within pre-existing thermal networks
- Implement *MERESS* to identify specific state-owned buildings ideal for installation

If implemented, these recommendations would give the state the greatest long-term environmental improvement for each dollar spent.

Benefits to California

California has already received several benefits from this contract:

- Californians have gained access to a simulation tool, the *MERESS* model, which can be run off most computers, that allows them to evaluate installing a FCS in a particular California building or town.
- Reading this report and running the *MERESS* simulation tool allows policy makers, FCS manufacturers, and building owners to gain a better understanding of how to design, install, and control FCSs to maximize reductions in GHG emissions and costs.
- The *MERESS* model helps users make more informed decisions about the trade-offs among three important, but often competing goals: GHG emission reductions, cost savings to building owners in procuring electricity and heat, and increasing FCS manufacturer sales revenue.
- The *MERESS* model shows fundamentally unique and important engineering approaches to designing, installing, and operating FCSs. Although these approaches have not typically been pursued by FCS developers or building owners, each can gain financial savings and environmental benefits by implementing them.
- Californians have gained a third-party, independent, expert evaluation of CO_2 emissions and costs from FCSs. In so doing, this research effort has reduced the asymmetry of information between technology developers and implementers, lessened a significant market failure in the commercialization of a productivity-enhancing technology, and aided its potential economic growth.

- Californians have gained a more accurate GHG emission inventory (see Attachment I) and well-informed advice on how to improve GHG accounting procedures and historical data series.

1.0 Introduction

California is approximately the world's 7th largest economy, and the 12th largest greenhouse gas (GHG) emitter. 22% of its emissions emanate from the electric power sector. The California Global Warming Solutions Act of 2006 (Assembly Bill (AB32)) requires that the state reduce its GHG emissions by 2010 to the 2000 levels, and by 2020 to the 1990 levels, while the California Governor's Executive Order S-3-05 mandates that by 2050, emissions must be 80% of 1990 levels (Executive Order S-3-05 2005, California Global Warming Solutions Act of 2006 2006).

GHG emissions and energy use could be reduced significantly through the use of stationary fuel cell systems (FCSs). Stationary FCSs are small scale power plants that can provide both electricity and useful heat directly to buildings with low emissions. Currently, U.S. electric power plants waste on average 68% of the available energy in their fuel, and boilers further waste 28% on average (Da Rosa 2003). These traditionally separate processes of 1) electricity generation and 2) useful heat recovery can be combined in a single process, known as cogeneration or combined heat and power (CHP). CHP plants can produce the same quantity of electricity and recoverable heat using less fuel and producing less GHG emissions. Power plants that create electricity close to the buildings they serve are referred to as distributed generators. The research presented here delineates the most effective ways to use stationary FCSs as distributed cogenerators to reduce GHG emissions at reasonable cost.

The primary energy problem addressed in this analysis is the design of novel networks of distributed CHP FCSs for reducing GHG emissions. Distributed CHP FCSs are being built in California under the statewide Self-Generation Incentive Program (SGIP) and the Distributed Energy Strategic Plan (PG&E 2007; Tomashefsky et al. 2002). The Maximizing Emission Reductions and Economic Savings Simulator (*MERESS)* optimization tool was developed and deployed to allow users to evaluate different strategies for installing and operating distributed CHP FCSs in California buildings. The *MERESS* model allows users to evaluate the electricity and heat supplied by networks of FCSs against real-time electricity and heating demand in California buildings. The *MERESS* model combines 1) engineering data describing the real-world operation of FCSs with 2) dynamic energy demand data from California residences, office buildings, and industrial facilities. The *MERESS* model allows users to evaluate the operation of these systems in different network configurations against the resultant change in GHG. The *MERESS* model allows a user to optimize the network's design either to minimize GHG emissions for electricity and heat provision or to minimize energy costs.

A unique aspect of the research is the analysis of FCSs in networks. Almost all previous studies of FCSs assume that they operate in a *stand alone* mode, with a single FCS providing electricity and heat to a single building. By contrast, the *MERESS* model enables a user to analyze these systems as either stand-alone or networked. A networked FCS can send its electricity via a local low-voltage distribution grid to surrounding buildings (not just a single building) and can convey its heat to multiple buildings via a local district heating network, composed of water or steam pipes. The *MERESS* model enables users to quantify the degree to which networked operation affects GHG emissions and costs. The *MERESS* model is intended to help critically guide California researchers developing fuel cells to make design trade-offs, California engineers building FCSs to prioritize design goals, and the state of California addressing climate change to create appropriate GHG emission and energy legislation.

This project's original, approved scope was defined to focus on FCSs exclusively, and not other types of distributed generation, for several reasons. FCSs have the highest electrical efficiency and lowest emissions of all distributed generators. They are the only distributed generation technology that has met California's strictest air pollution requirements. By contrast, microturbines fueled by natural gas have very low electrical efficiencies (around 20%) and higher air pollution emissions than FCSs. Similarly, internal combustion engines systems fueled by natural gas have a relatively low electrical efficiency (around 30%), higher air pollution emissions than FCSs, and noise abatement and maintenance concerns. For these reasons, this project focuses entirely on FCSs.

1.1. Motivation: Reduced Energy Consumption

1.1.1. Distributed CHP FCSs Can Be More Efficient than Conventional Power

Stationary FCSs can be designed as distributed CHP generators. Distributed generators are decentralized generators located near the buildings they supply. They send their electricity both to a nearby building site with an onsite source of demand and to a local low-voltage distribution network to supply more buildings. Existing neighborhood electricity distribution networks can be retrofitted to connect with distributed generators. **Figure 6** shows a simple example of a distributed network of three fuel cell systems providing electricity via low voltage distribution lines to the neighboring six buildings (Colella 2002(a)). Distributed generators may also operate in a CHP mode, whereby they convey their heat to their immediate building site as well as to surrounding buildings via steam or hot water heating distribution lines. By contrast, conventional generation is usually produced far from electricity demand sites and, therefore, results in high transmission losses and low in-use heat recovery rates. In the US, conventional power plants do not typically recover heat for space and hot water heating due to the large distances between heat supply (in remote locations) and demand (in populated areas).

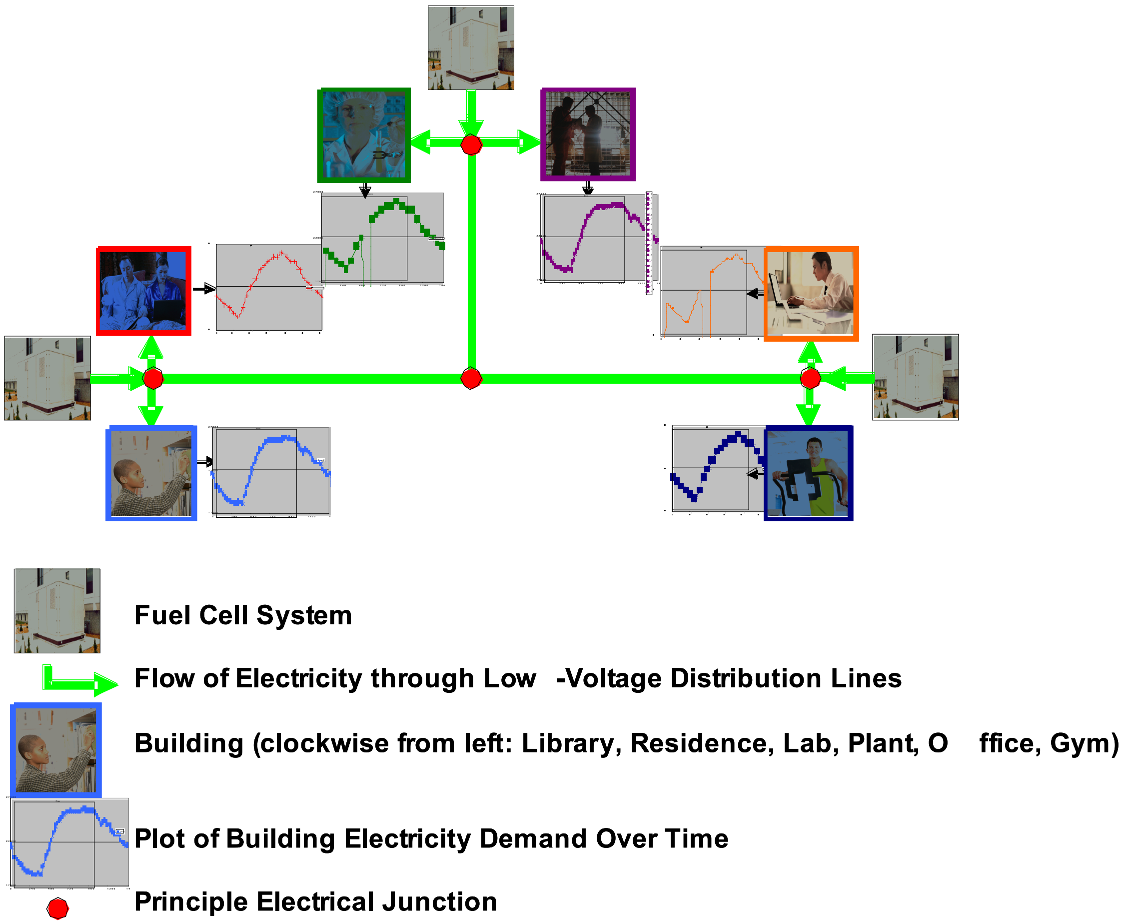


Figure 6: Fuel cell systems situated as distributed generators

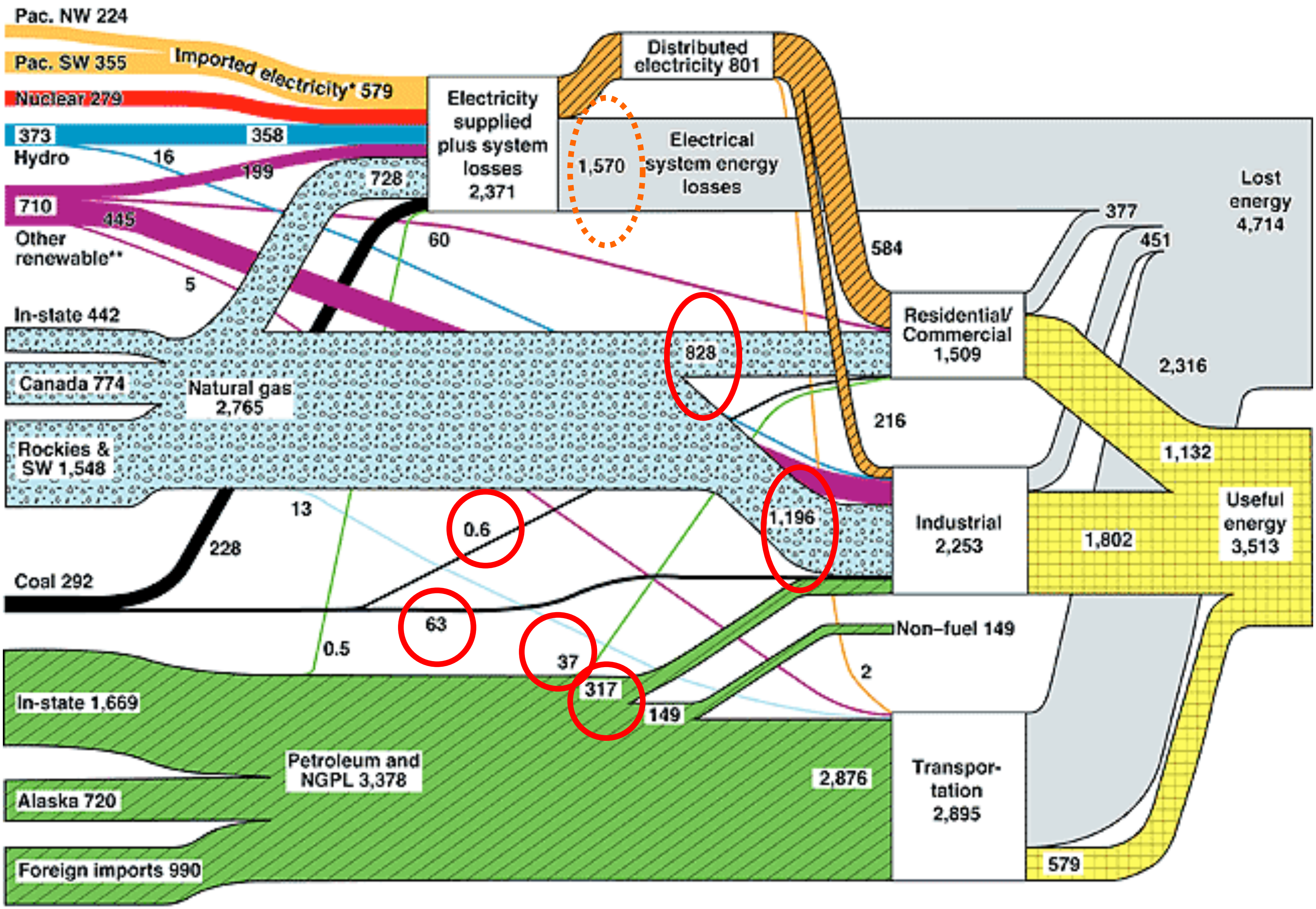
1.1.2. Distributed CHP FCSs Can Recover Heat at Higher Efficiency

Distributed CHP FCSs can recover heat at a high rate and consequently can reduce fuel consumption and GHG emissions significantly. Because distributed CHP FCSs are situated close to the buildings they serve, they can deliver a portion of their heat to buildings for hot water and space heating needs. By contrast, the second law of thermodynamics limits the effectiveness of transferring heat across the large distances commonly found between conventional generators and the buildings where heat is demanded. By way of example, a distributed generator such as a CHP FCSs may produce 40 units of electrical power and 50 units of heat that can be recaptured for a building's heating for every 100 units of fuel energy it consumes. Potentially, 90% of the energy in the fuel could be usefully directed. By contrast, a conventional power plant typically produces 32 units of electric power with 100 units of fuel energy and discards the 68 units of heat available (EPA 2002; Da Rosa 2003). On top of that, in conventional heat generation, additional fuel must be consumed in furnaces or boilers to produce heat for hot water and space heating. A typical furnace may produce 72 units of usable heat for every 100 units of fuel consumed, with 28 units wasted in the processes (EPA 2002; Da Rosa 2003). Thus, by combining the production of electricity and heat, and situating generators close to the sources of demand, distributed generators can significantly reduce fuel consumption and consequently GHG emissions. An additional benefit of distributed power is greater security of uninterrupted electricity supply, in the event of a grid outage.

1.1.3. California Can Save 1/6th of Energy Demand with Distributed CHP FCSs

The potential energy savings from distributed CHP is approximately 1/6th of total energy needs in California. The primary flows of energy in California are shown in the energy flow chart of **Figure 7** (Kaiper 2003). This energy flow chart shows energy supplied on the left side and energy needed for use on the right side. This figure shows that the quantity of energy lost as heat at centralized electric power plants (left side) is approximately equal to the quantity of energy needed for use in residential, commercial, and industrial buildings (right side). The quantity of energy lost as heat at electric power plants is about 1,570 Trillion British Thermal Units (BTU), shown in the dashed circle. As shown in the solid circles, the quantity of energy consumed to produce heat in residential and commercial buildings is about 865.6 Trillion BTU (828 + 0.6 + 37), and, in industrial buildings, it is about 1,576 Trillion BTU (1,196 + 63 + 317), for a total of 2,442 Trillion BTU. If centralized electricity generation was shifted to decentralized, distributed CHP near buildings, the 1,570 Trillion BTU of heat that is currently lost at centralized plants instead could be used to displace a similar quantity of heat generation at buildings, subject to heat transfer limitations. Approximately 90% of this available heat could be recovered for useful purposes, if it was generated at distributed plants close to buildings. The total energy savings could be about 1,413 Trillion BTU (90% X 1,570 Trillion BTU), or $1/6^{th}$ of California's total energy consumption. In this way, **Figure 7** underscores a primary motivation for moving to greater levels of distributed CHP FCSs. (An analysis of federal data yields similar results: a potential energy savings of around $1/5^{th}$ of total consumption.)

Figure 7. California energy flows in 1999, with a net primary resource consumption of 8375 trillion BTU (8.375 Quads) (Kaiper 2003)



1.2. Motivation: Reduced GHG Emissions

1.2.1. Distributed CHP FCSs Can Reduce GHG Emissions by 65% or More

If CHP FCSs replace existing electricity and heat generators, they can significantly reduce GHG emissions, if they are fueled by either natural gas or hydrogen, in principle. This point is illustrated with some back-of-the-envelope calculations shown in **Table 1**. **Table 1** compares emissions of the primary greenhouse gas, carbon dioxide (CO_2), from five different configurations of electricity and heat generators. The first three cases are for current generation technologies; the last two are for CHP FCSs. The first three cases show a worst, average, and best case for current generation. The last two show cases for CHP FCSs fueled by either natural gas or hydrogen. In each case, the generators produce the same quantity of heat and electricity, to create a fair comparison. (None of these cases is the base case cited previously in the Executive Summary in regards to the comparative scenarios and strategies.)

	Source of Electricity or Heat	CO_2 Emission Factor (g/kWh_e or g/kWh_heat)	Electricity Production (MWhr)	Heat Production (MWhr)	CO_2 Emissions (kg)
Case 1: Conventional System	Coal Power Plant with Steam Turbine	860	2	0	1720
	Coal Fired Boiler / Furnace	410	0	1	410
	Total		2	1	**2130**
Case 2: Average System	Mix of 1999 US Electric Generation Plant	600	2	0	1200
	Boiler / Furnace (72% efficient)	280	0	1	280
	Total		2	1	**1479**
Case 3: Advanced System	Cogenerative Combined Cycle Gas Turbine	380	2	0.71	760
	Boiler / Furnace (92% efficient)	219	0	0.29	64
	Total		2	1	**824**
Case 4: Fuel Cell System fueled by natural gas	Cogenerative Molten Carbonate Fuel Cell	373	2	1	**746**
Case 5: Fuel Cell System fueled by renewable hydrogen	Cogenerative Molten Carbonate Fuel Cell	0	2	1	**0**

Table 1. Comparison of CO_2 emissions from conventional generators and fuel cells

Each of the cases examines a different combination of technologies, operating at different efficiencies, for electricity and heat provision. In Case 1 (the "worst" case scenario for CO_2 from conventional generation), coal power plants produce all electricity, and coal boilers make all heat (Porteous 2000). In Case 2 (the "average" case), the average mix of electric power generators in the US in 1999 makes all electricity, and natural gas boilers of average performance produce all heat (EPA 2002; Da Rosa 2003). In Case 3 (the "best" case), CHP combined cycle gas turbine (CCGT) produce all electricity and a portion of the heat, at an electrical efficiency (defined as the net electrical energy out divided by the fuel energy in) of 53%. Any remainder heat is provided by advanced natural gas boilers (EPA 2004). In Case 4, one type of CHP FCS, a molten carbonate fuel cell (MCFC) system, consumes natural gas and produces electricity at 54% electrical efficiency, and also heat. (Ghezel-Ayagh et al. 2003). This system is based on the reported performance of Fuel Cell Energy Inc.'s MCFC (Brdar et al. 2006). The ratio of useful thermal recovery to electrical power (a term known as the heat-to-power ratio) is approximately one over two (0.5) for this system. In Case 5, a MCFC of similar design consumes biogas or hydrogen derived from a renewable source. If hydrogen is produced from water via electrolysis, and if the electricity for the electrolysis is provided by renewable energy devices such as wind power or solar photovoltaic cells, no CO_2 emissions are created during the production of the hydrogen fuel. Biogas is a gas produced by the anaerobic digestion or fermentation of organic matter such as sewage sludge, manure, or municipal solid waste. Biogas is typically comprised of 50-75% methane (CH_4) and 25-50% CO_2. The consumption of biogas results in a net reduction in CH_4 and CO_2, both GHG, that would otherwise be emitted into the environment. In Case 3, the CHP CCGT are situated far from the buildings they serve, in comparison with the distributed CHP FCSs, such that only 50% of their available waste heat is recovered, compared with 60% for the FCSs. (A shorter distance between generators and buildings leads to higher heat recovery rates in a district heating network.)

As shown in **Table 1**, a CHP FCS consuming natural gas or renewable hydrogen or biogas can significantly reduce CO_2 emissions. A comparison of Cases 1 and 4 in **Table 1** shows that, when replacing conventional generators consuming coal, a CHP FCS can reduce CO_2 emissions by 65%. A comparison of Cases 2 and 4 shows that, when replacing the average mix of stationary electric power and natural gas boilers, a CHP FCS can reduce CO_2 emissions by 50%. A comparison of Cases 3 and 4 shows that, when replacing CHP CCGT (the lowest carbon-emitting power and heat generation technologies), a CHP FCS can reduce CO_2 emissions by 10%. Finally, as shown by Case 5, a CHP FCS fueled by renewable hydrogen or biogas can have zero net CO_2 emissions, even over the life cycle of the related processes of hydrogen generation, distribution, and supply (Colella et al. 2005(a)). **Table 1** quantifies the degree to which a CHP FCS can reduce CO_2 emissions under different scenarios.

Table 1 does not address the extent to which a CHP FCS consuming biogas could reduce GHG emissions. The American fuel cell manufacturer Fuel Cell Energy Inc. and the German manufacturer MTU have built, installed, and operated a few pre-commercial biogas FCSs in the last few years. One unit of CH_4 is estimated to have 23 times the global warming impact as a unit of CO_2 over a 100-year period (IPCC 2001). When a CHP FCS consumes the CH_4 in biogas, it prevents this molecule from being emitted into the atmosphere and having 23 times the global warming impact as a molecule CO_2. If this "net reduction" in global warming impact is included, a biogas CHP FCS could be treated as having a net negative emission factor, not just one with a value of zero. Furthermore, if a FCS effectively consumes biogas CH_4 to produce electricity, this biogas FCS displaces some CO_2 emissions that would have emanated from a fossil fuel power plant. This further reduction in CO_2 emissions through displaced electric power must also be credited to the biogas FCS. In other words, the incentive for biogas CHP FCS over biogas flaring is the additional displaced CO_2 from electric power plants and boilers. Flaring does not displace CO_2 from these sources. Current federal and California state GHG emission inventories do not yet include the net negative impact of power generators consuming biogas; to simplify the calculation, they assume a net zero impact. The authors of this study recommend a change in federal and state GHG accounting procedures to include the net negative effect of biogas power generators.

1.2.2. California Can Significantly Reduce GHG with FCSs only with CHP

To better direct our research trajectory, it was necessary to conduct a background analysis to quantify the degree to which CO_2 emissions would increase or decrease in California as a result of the introduction of FCSs, under different scenarios. As a result of this analysis, we focused our model development on a particular type of low-temperature FCS, the Phosphoric Acid Fuel Cell (PAFC) system. With these systems, our background analysis showed that effective heat recovery is pivotal for reducing CO_2 emissions.

For this background analysis, we estimated the change in CO_2 emissions in California with the implementation of CHP FCSs, compared with historical California power generation. To do this, the authors investigated historical CO_2 emissions from electric power generation in California using federal and state databases. In the process of doing so, the authors discovered a significant discrepancy between state and federal databases, approximately 34% on average over the past 15 years. The authors investigated the source of this discrepancy and informed the California Energy Commission (CEC) of some errors in its database. An abstract summarizing this analysis is presented in Appendix A.[1] The authors' analysis of the CEC database was additional to what the authors were contracted to provide, and only undertaken to ensure a fair comparison of fuel cells with conventional systems. A thank you letter from the CEC for a portion of this analysis is shown in Appendix B. Based on this analysis, the authors believe that the most complete baseline for historical CO_2 emissions in California from the electric power sector is the federal baseline data. Using the federal baseline emissions to eliminate discrepancies, the authors quantified the change in CO_2 emissions with the introduction of FCSs compared with historical California power generation. An example plot from this analysis is shown in Figure 8.

Figure 8 illustrates results from this background analysis. It is for a hypothetical scenario in which four different types of FCSs replace 100% of the electricity in California. Figure 8 shows the change in CO_2 emissions if FCSs replaced 100% of power generation for California, including both in-state generation and imported electricity. The analysis evaluated the period between 1990 and 2004. Figure 8 shows an example plot for the month of January 1990 for the change in CO_2 emissions in metric tonnes (MT) per month (Mo) per county (Cty). This case is especially relevant for organizations in California that are interested in reducing their CO_2 footprint and want to decide if it would be better for them to connect to the California grid or to install a FCS. The analysis assumes that the FCSs consume natural gas fuel, do not operate cogeneratively, are electrically networked – connected to the distribution grid allowing inflow and outflow of electricity, operated with a fixed heat-to-power ratio (FHP), are non-load flowing (NLF), and operate at their maximum electrical efficiency (□e_max). This analysis evaluates four FCS types: Proton Exchange Membrane (PEMFC), with a □e_max ≈ 32%, PAFC with a □e_max ≈ 37%, Molten Carbonate Fuel Cell (MCFC) hybrid w/ downstream gas turbine with a □e_max ≈ 54%, and Solid Oxide Fuel Cell (SOFC) pressurized hybrid w/ downstream turbine with a □e_max ≈ 60%. A detailed explanation of the different fuel cell types is available in O'Hare et al. (2006). The plot applies a sigmoid function to the data to highlight small variations in the low positive and low negative data values. The blue and green shades are "good," indicating reductions in CO_2 emissions with FCS implementation relative to the status-quo case of the historical California grid; the red and black shades are "bad," indicating an increase in CO_2 emissions with FCSs installed relative to the same status-quo case. The colors in the plots show one example month in January 1990. The numbers next to each plot state the total cumulative change in CO_2 over 15 years from 1990 to 2004 in Million Metric Tonnes

[1] Additional information is available from the authors.

(MMT). For PEMFC, PAFC, MCFC, and SOFC, these values are +848 MMT, +549 MMT, -54 MMT, -168 MMT, respectively. Without cogeneration and effective heat recovery, PEMFC and PAFC would increase CO_2 emissions from the California grid by +848 MMT and +549 MMT, respectively, over the 15 year period, if they are not operated cogeneratively with effective heat recovery. (Appendix C outlines additional details of the data sources and methodology for creating Figure 8.)

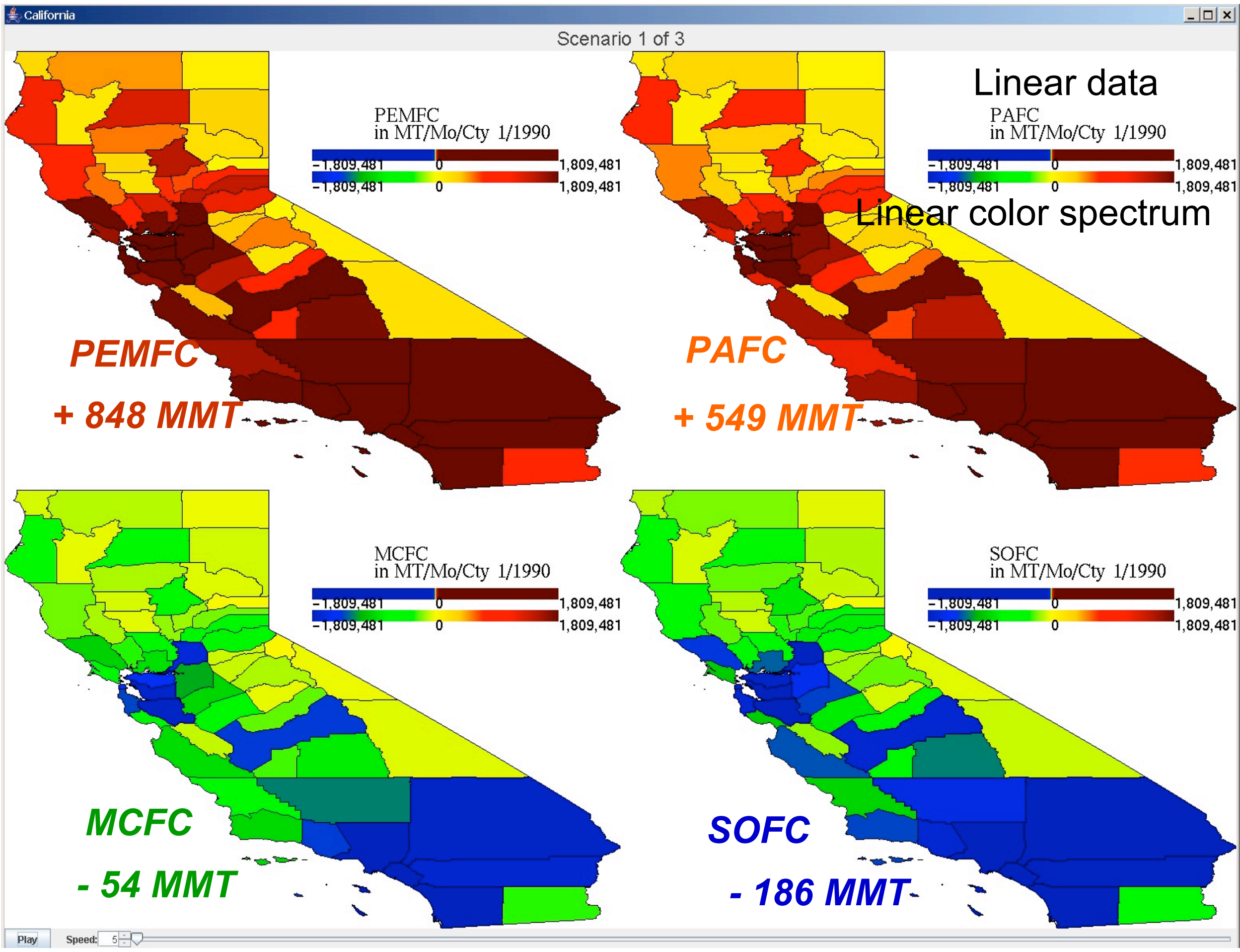


Figure 8: Change in CO_2 in California by county with different fuel cell types installed

A primary take-away point from the analysis shown in Figure 8 is that if PEMFC and PAFC are to reduce CO_2 effectively in California, they must be operated cogeneratively with high effective heat recovery. Without highly effective heat recovery, their implementation could increase CO_2 emissions in California relative to the California mix of electric power. As a consequence of this analysis, although the MERESS model is capable of evaluating all FCS types, the authors chose to run the *MERESS* model to evaluate one of the most challenging FCS types to implement for CO_2 reductions, the PAFC system. The *MERESS* model adds the most value in addressing installation strategies that depend on effective cogenerative heat recovery for CO_2 reductions. Consequently, the authors implemented *MERESS* model to help answer this more challenging question. The results from running the *MERESS* model are shown in the subsequent chapter entitled *Results*. As the analysis above shows, the PAFC can be quite tricky to implement; only if these systems recover heat effectively to serve a source of thermal demand, will they be able to reduce CO_2 emissions in California.

Please note that this "status-quo" case of the historical California grid is an entirely different data set than the data set referred to as the "base case" in all other sections of this report. The California grid was not used as the "base case" in the remainder of the report for three main reasons: First, lead research and reporting organizations continue to differ on the best data sets to describe CO_2 emissions from the California grid. Second, the best available data are very poor for CO_2 emissions from imported electricity. Third, in 2007, the California Air Resources Board (CARB) continued to revise the state's version of this data set. Due to the controversy, poor data quality, and continual evolution of this "status-quo" data series, the authors chose a more stable "base case" for later comparisons. For the model presented later in this report, the "base case" refers to a scenario in which no FCSs are installed, and heat and power are provided exclusively by a competing generator or set of competing generators. Because no fuel cells are operated in the base case, the cost of fuel for fuel cells in the base case is zero. The model's user can define the characteristics of this competing generator. For the Results present in this report, the "base case" refers to a scenario in which all heat and power are provided by a high-performance CHP CCGT plant.

1.3. Motivation: The Necessity of Detailed, Real-Time Simulations

In theory, FCSs can reduce energy consumption and GHG emissions. However, in practice, their potentially positive economic and environmental impact depends on the design of the FCS, the control strategy of the FCS, and the design of the network in which the FCSs operate. For example, the overall in-use efficiency of FCSs can vary between 40% and 90%. This in-use efficiency can vary with hourly, daily, and seasonal demand for electricity and heat. This in-use efficiency depends on whether the recoverable waste heat of these FCSs matches the thermal demands of the buildings it serves, which in turn depends on the control strategies of the FCSs and of the network of FCSs. As another example, as the control strategy of a FCS and the design of its network change, so changes the capacity utilization of these systems, which can easily vary between 20% and 100%. Capacity utilization, or load factor, is defined as the percentage of the time a power plant is operating at its rated maximum power (its maximum capacity), and is a primary determinant of the costs of energy delivered. As a result, the financial and environmental effectiveness of FCS is best determined by evaluating FCSs within the particular energy areas, networks, and buildings they may serve.

Automakers evaluate their vehicles by testing them against driving cycles, records of desired vehicle speeds over time. **Figure 9** shows an example of a driving cycle from the U.S. Environmental Protection Agency (EPA) (EPA 2007). These driving cycle tests can be used to reveal information about the in-use vehicle performance, such as the engine efficiency, mileage, transmission efficiency, and emission profile. Engineers then use these results to improve vehicle design. Similarly, the *MERESS* model tests the performance and costs of distributed CHP FCSs against the electricity and heat load curves of California towns and buildings to guide design improvements. **Figure 10** shows one example of such a load curve for a building, the electricity demand over every minute of a day for a residence (Advantica Ltd. 2003).

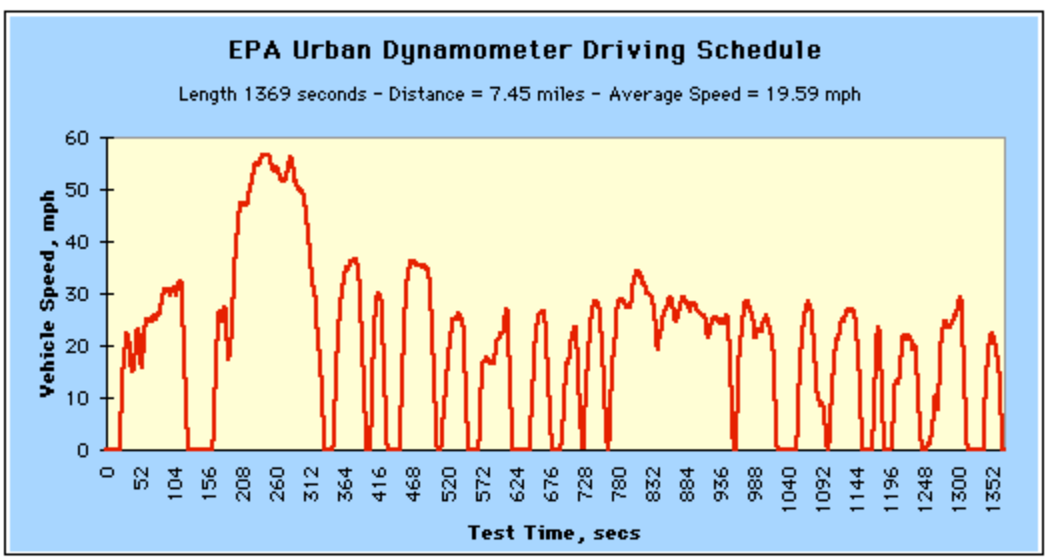


Figure 9: U.S. Urban Driving Cycle, a test of desired vehicle speed over time (EPA 2007)

Table 1 on page 15 and Figure 8 gives useful estimates of GHG reductions under different cases. However, the degree to which a fuel cell network genuinely achieves these GHG reductions depends on that particular network's in-use electrical and heat recovery efficiencies. In turn, these efficiencies depend on the design of the FCS network. A primary goal of the *MERESS* model is to use relatively inexpensive simulation studies to identify more financially and environmentally effective ways to design and install this FCS network.

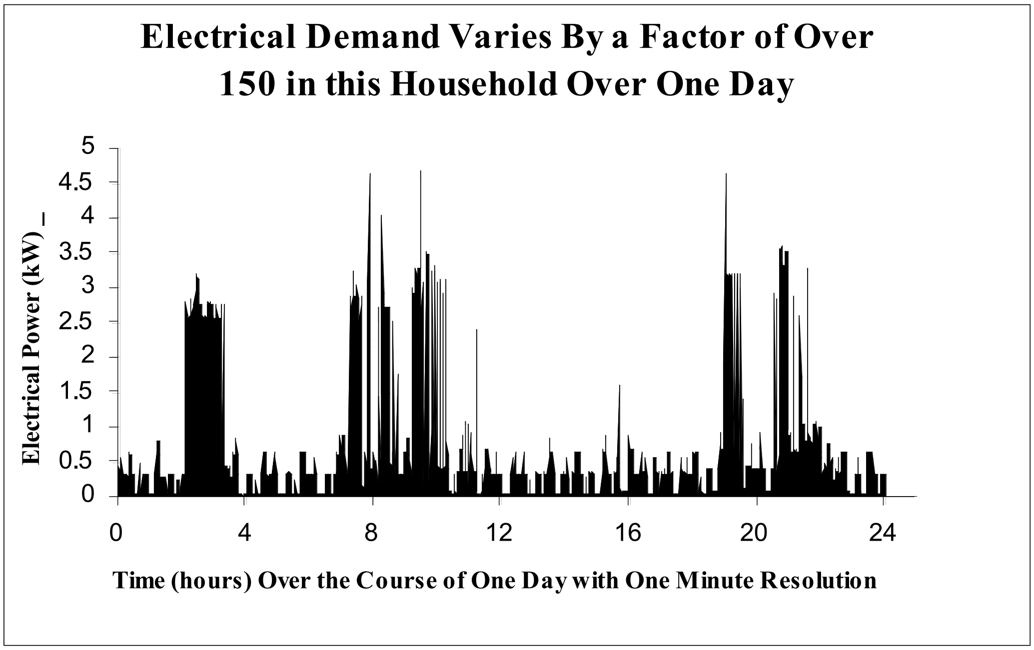


Figure 10: **Real-time electricity demand from a detached house the weekend of May 6, 1996. (Colella 2002(a)).**

MERESS can quantify the extent of the GHG reductions and indicate design and control strategies for augmenting emission reductions. The extent of these GHG emission reductions depends on the nature of the building load curves and the design and control strategy of the network. These two dependencies are illustrated with examples below.

Overall network efficiency depends highly on building energy demand profiles. For example, one building demand parameter is its ratio of heat to electricity required. This ratio can be referred to as a building's heat-to-power ratio, which varies over time by hour, time of day, and season. If the building's heat-to-power ratio matches well with that of the FCS, the FCS network's in-use efficiency can be high. In Table 1, Fuel Cell Energy's MCFC exhibits a heat-to-power ratio that precisely matches that of the buildings it serves. In practice, the heat-to-power ratio of a FCS will not continually match that of the buildings' it serves over all time. (A primary exception to this is if the FCS is designed with a variable heat-to-power (VHP) ratio and the building's demand profiles remain within this VHP range. The concept of VHP is explained in detail in the next sub-section.) When the FCS and building exhibit heat-to-power ratios that match more over time, the overall in-use efficiency of the FCS will be higher and their GHG emissions lower.

Furthermore, certain types of FCSs with a particular range of heat-to-power ratios may serve a particular set of buildings more efficiently than others. Table 1 shows that Fuel Cell Energy's MCFC tends to operate with a heat-to-power ratio of one to two. By contrast, United Technologies Inc.'s (UTC) PAFC systems tend to operate with a heat-to-power ratio of two to one (UTC Fuel Cells 2001; UTC Fuel Cells 2003.) Consequently, the MCFCs and the PAFCs may be best suited for installation in different buildings with different load curves and heat-to-power ratios. This example illustrates the importance of carefully analyzing an individual building's load curves and heat-to-power ratios over time. For this reason, the *MERESS* model incorporates detailed electricity and heating load curve data from 30 different California buildings. These load curves capture different energy demand behavior over time.

Overall network efficiency also depends highly on the design and control of the network. FCSs can be operated with a variety of control methodologies. These include stand alone operation, electrically and thermally networked operation, heat load following, electricity load following, constant electrical and thermal output, variable heat-to-power ratio, and fixed heat-to-power ratio. Each of these control strategies is carefully explained in the next sub-section. Each has a different effect on network efficiency, fuel consumption emissions, and costs. By way of example, FCSs may be able to match their instantaneous supply of heat with that demanded from buildings more effectively by operating with a variable heat-to-power ratio. With this feature, FCSs may be able to provide the same amount of electricity and heat at a lower fuel consumption rate and with lower GHG emissions. Control strategy, coupled with design, can compensate for imperfect matchups between FCS design and host building characteristics. *MERESS* helps users identify these more viable control strategies and designs through inexpensive simulations.

1.4. Motivation: Addressing Technical Barriers and Knowledge Gaps

Corporations have conducted their own evaluations of the economics of FCSs (Plug Power 2000; Arthur D. Little 1995; Behling 1999). However, these studies are likely to reflect the internal biases and vested financial interests of the corporations commissioning them. As a result, these studies must be reviewed critically. At the same time, it can be difficult to find experts with a detailed knowledge of the underlying technology's performance who are also unbiased and not financially incentivized to review a technology in either a positive or negative light. The bifurcation between unbiased technology evaluators and those with a detailed understanding of the technology's performance can lead to a significant market failure in innovation. This market failure may skew investments and research in either direction, either indicating too much or too little investment and research would be valuable. The asymmetry of information between investors and technologists can create a significant market failure in appropriate investments in technology and, subsequently, in commercialization of productivity-enhancing technologies. Such a market failure can lead to lower rates of economic growth.[2] This type of market failure can be significantly attenuated by independently-funded, unbiased, and well-informed academics studies, such as the one conducted here.

The most apparent limitation of previous academic studies on stationary FCSs is their assumption that these systems would operate stand-alone (Kreutz 2000; Seymour 1998; Thomas 1999; and Gray 1999). None of these studies assumed that FCSs would be integrated into networks. They assumed that one FCS would power one individual building's electrical load in stand-alone mode, not connected to electrical or thermal distribution networks, other buildings,

[2] Economic growth as defined by the Solow Growth model; for example see Solow, Robert M. "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics*, August 1997.

or distributed generators. By contrast, the research presented here overcomes this limitation by evaluating FCSs in networks.

Other academic studies of stationary FCSs concluded that their economics is heavily impacted by their capacity utilization (Thomas et al. 1999; Thomas et al. 2000). An individual power plant serving a single building can experience low capacity utilization, because demand for energy can vary significantly by time of day and season. For example, **Figure 10** illustrates that electrical demand in a typical British household varied by a factor of 156 during a single day in May (Advantica Ltd. 2003).

By contrast, FCSs that are electrically and thermally networked and serving multiple buildings can experience higher capacity utilizations, because demand for energy can vary less over a larger set of buildings, so long as energy demand in those buildings is not highly correlated. A benefit of connecting FCSs to distribution networks is that the building demand profiles level off with a greater number of buildings, so long as energy demand among buildings is not highly correlated. The combined profiles exhibit less daily demand variability. For this reason, centralized generators serving a large-scale regional network can achieve high capacity utilizations. British journals on energy economics sometimes refer to this effect as "economies of scale in generation." However, it might be more precise to refer to it as "economies of scale in networking." The *MERESS* model presented here allows users to test the hypothesis that small generators can achieve the same "economies of scale in networking" on a smaller network.

Industrial studies have also not yet pursued the research presented in this report. Many stationary FCS manufacturers have tended to focus on operating FCSs as stand-alone systems only. They have generally not modeled these systems "outside the box" of the FCS, and connected to thermal and electrical networks, as well as each other. Also, many stationary fuel cell developers, such as Ballard Inc. and Bloom Energy Inc. (formerly Ion America Inc.), have focused on developing FCS primarily as electricity generators, not as CHP systems. For example, Ballard's former Chief Technology Officer, Dr. Charles Stone, explained that FCS developers such as Ballard have not cultivated their ability to recover heat from stationary FCSs or their ability to operate FCSs in networks (Stone 2004). As of 2005, Ballard had produced only one 250 kWe system that could operate as a CHP system to recover heat, had only operated this stationary system stand-alone, and had not researched the benefits of networking (Sexsmith 2004).

Like Ballard Inc. and Bloom Energy Inc., many fuel cell developers have focused solely on building "electricity generating boxes." Their intention has been to then sell these boxes to customers who they hope will invent uses for them. This approach has not resulted in significant FCS market penetration, in part because many American utilities are only beginning to develop a core competency in distributed generation and in CHP. Utilities have not chosen this development route for several reasons. These reasons include, but are not limited to, traditionally low fuel prices in the U.S., legal restrictions, Not In My Back Yard (NIMBY) attitudes of residents toward traditional combustion power plants located close to their homes, and the higher air pollution-related health impacts from locating power plants closer to people. As a result of few such partnerships between utilities and FCS developers, FCS manufacturers have not cultivated an expert understanding of how to design, operate, and configure their FCSs to mitigate GHG, much less to analyze optimal operating strategies for them within networks for reducing GHG emissions. As a result, the *MERESS* model is avant-garde and potentially game-changing for the industry.

1.5. Background: Game-Changing Designs for Installing FCSs

The research team expanded the realm of possibilities for FCS installation and control by identifying and examining unique design options, which commercial industry has not typically pursued. FCSs can be installed and controlled using innovative designs, such as

- Stand alone (SA) or networked (NW),
- Heat load following (HLF), electricity load following (ELF), or no load following (NLF), and
- Variable heat-to-power ratio (VHP) or fixed heat-to-power ratio (FHP).

Most prototype FCSs today are installed as SA, NLF, and FHP. By contrast, this analysis enables fuel cell developers and building owners to think outside of this confined box.

1.5.1. Stand Alone (SA) or Networked (NW)

Networks are inter-connected energy distribution channels for conveying electricity or heat. If FCSs are SA, they cannot convey excess electricity or heat to other buildings. If SA, they can not convey excess electricity into low-voltage electricity distribution grids to send this excess to other buildings where additional electricity demand might exist. They also cannot convey excess heat into thermal networks of steam heating pipes to send unconsumed heat in one building to other buildings that may have a need for heat. **Figure 11** shows FCSs feeding electricity (dashed, orange arrows) and heat (solid, green arrows) into multiple buildings in an energy consuming area, a California town resembling a campus for a college, corporation, or government entity entity, referred to in this report as Campustown. Campustown's building load curves are based on those from buildings on the Stanford University campus.

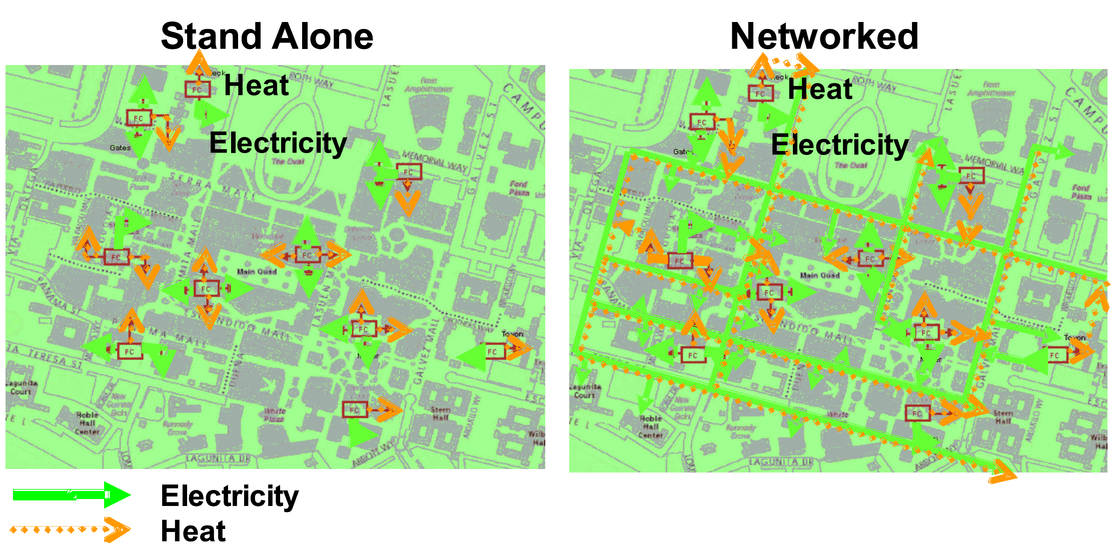


Figure 11. Comparison of SA and NW operating strategies

Figure 11 compares SA FCSs with NW ones. SA systems are defined here as not being able to convey either excess electricity into the low voltage electricity distribution grid or excess heat into a hot water or steam heating piping network to reach other buildings. While SA systems feed only nearby buildings, NW systems feed not only nearby buildings but also an entire energy network that serves dozens or hundreds of buildings. NW FCSs can convey their excess heat or electricity into electricity and heating distribution networks to reach other buildings. A primary benefit of operating FCSs as part of a network can be to increase the capacity utilization of each of the systems, an effect that can decrease the costs of the power plants. Distribution losses are typically close to 0% for electricity lines and around 8% for steam heating pipes across short distances in California (Murray 2007). The later depends on the climate region.

1.5.2. Heat, Electricity, and No Load Following (HLF, ELF and NLF)

Figure 12 compares three different FCS control strategies: HLF, ELF, and NLF. When a device is operated in a load-following manner, it produces only the amount of product demanded at that instant in time. The left side of **Figure 12** shows a FCS operating in a HLF manner; its output is primarily determined by the instantaneous heat demand of the building it serves. Its electricity is a by-product. **Figure 12** compares this control option with ELF, shown in the figure's center, in which the system's instantaneous electrical supply matches the instantaneous electrical demand of the building. The heat supply of the system is a by-product of the electrical supply. FCSs may include some electrical energy storage within their systems to enhance their ability to rapidly respond to changes in electrical load. For the NLF control option, the FCS produces a fixed quantity of electricity and heat over time, which does not vary with the amount of electricity and heat demanded by the building.

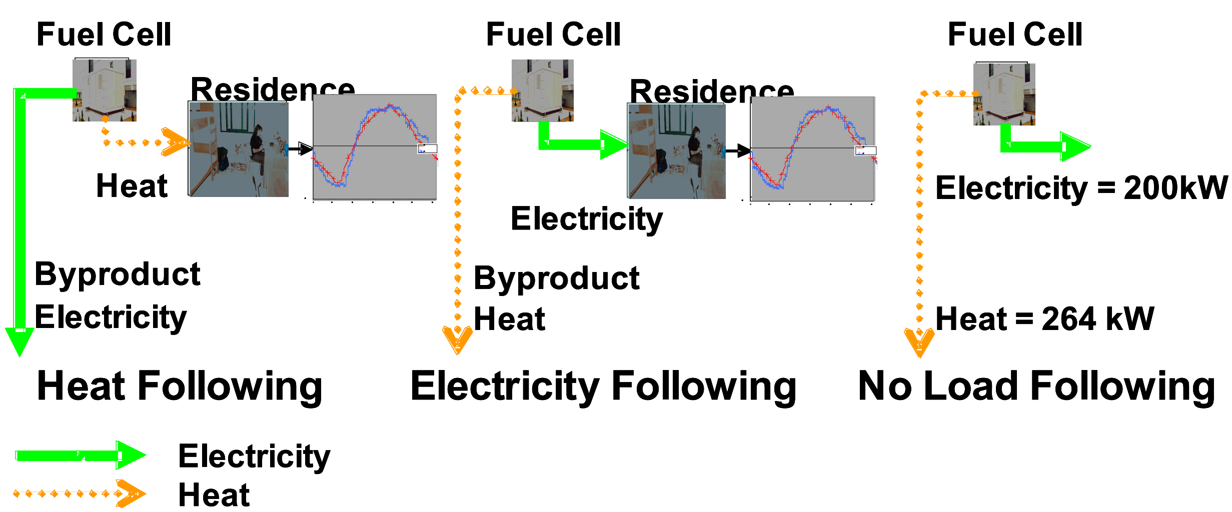


Figure 12. Comparison of load following operating strategies

1.5.3. Variable Heat-to-Power Ratio (VHP) or Fixed Heat-to-Power Ratio (FHP)

A CHP power plant produces recoverable heat and electricity in a particular ratio to each other. This ratio is known as the heat-to-power ratio (O'Hare, Cha, Colella, and Prinz 2006). A fixed heat-to-power ratio (FHP) indicates that the ratio of useful, recoverable heat to net electricity produced does not change with power output level, load cycle, or time. The heat recovery efficiency and the net electrical efficiency are constant. By contrast, a variable heat-to-power ratio (VHP) indicates that the ratio of useful, recoverable heat to net electricity produced can be intentionally changed at a given electrical output level in a short time. With a VHP, the system-wide heat recovery efficiency and the system-wide net electrical efficiency can be changed. An advantage of a VHP is that the system can be intentionally operated with a lower system-wide net electrical efficiency and a higher heat output level to meet a higher thermal demand from a building (such as for space heating during winter). FCSs with VHPs can change both the electrical and thermal output to more closely match electrical and thermal demand.

In early 2002, one of the author's published an article on the benefits of a VHP and five different methods for designing this feature into a FCS (Colella 2002(b)). After this publication, the German fuel cell company, MTU, owned by Daimler Benz, began to implement a VHP in its Molten Carbonate Fuel Cell (MCFC) system designs (MTU 2004). However, as of 2007, the concept of designing FCSs with a VHP has yet to spread widely among all commercial manufacturers.

Figure 13 compares and contrasts a FHP operating regime with a variable one. The data are based on the performance of a United Technologies Inc. 200 kWe PAFC System (UTC Fuel Cells 2001; UTC Fuel Cells 2003). Although this system is not currently designed to incorporate a VHP, it could be modified to do so, as explained in more detail in the next section. Between 100 and 200 kWe, the system normally has an approximately FHP of 1.3. This constant heat-to-power ratio is shown by the bottom line plotted in red and the linear slope over this range. The top most line plotted in blue shows that the operating region could be extended, up to a maximum heat-to-power ratio of 2.5, for example. Under a VHP operating strategy, the heat-to-power ratio could range from anywhere between 1.3 and 2.5 (the area of the figure bounded by the red and blue lines and populated by dark green arrows). In this way, a VHP extends a system's operating range. If systems are designed with a VHP, their heat to power ratio can be changed to accommodate changes in heat and power demand. This change in heat and power supplied is achieved by changing the way the system operates internally. This can be done by either "pulling a lever" or through another feedback loop, as explained next.

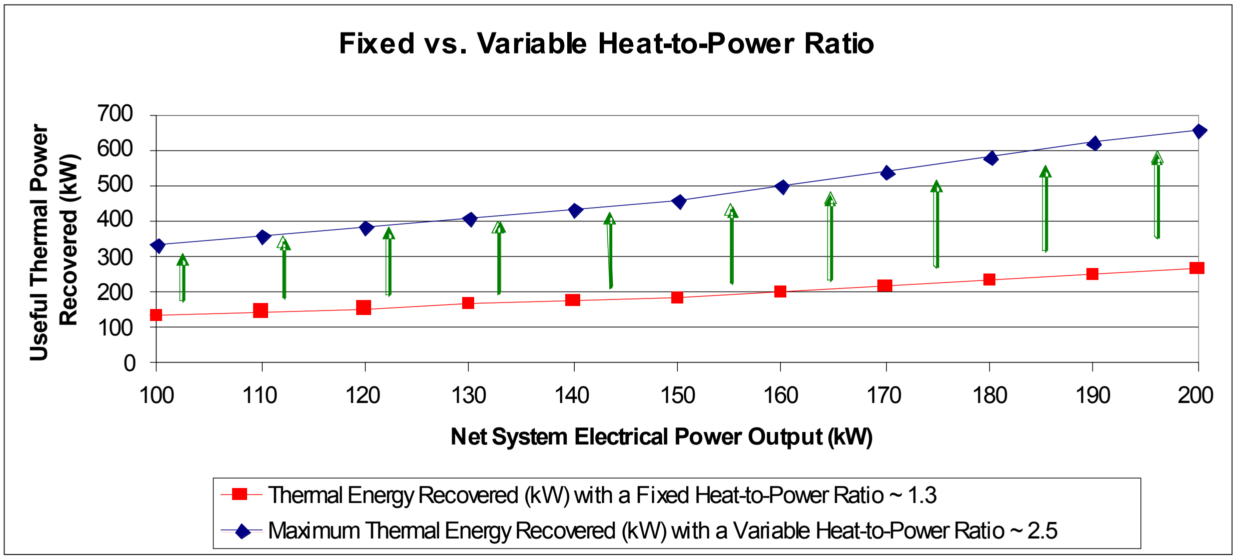


Figure 13. Comparison of fixed vs. variable heat-to-power operating strategies

1.5.4. Methods to Achieve a Rapidly VHP

A FCS can be designed to achieve a VHP in various ways (Colella 2002(b)). One of the simplest methods is to use the burner already installed in a FCS like the burner in a furnace or boiler, to provide additional heat through combustion of the primary fuel. A FCS will have at least one burner, often in the fuel processing sub-system, to provide heat for converting the fuel, often natural gas, into a hydrogen rich gas. The process is typically done catalytically, such that any air pollutants created are a fraction of what they would be in standard or high-performance boilers and furnaces. The United Technologies Inc. PureCell incorporates such a catalytic burner while also meeting the strictest California air pollution standards for stationary power (UTC Fuel Cells 2001; UTC Fuel Cells 2003). A FCS may have more than one burner, such as an anode-off gas burner, which consumes the unused portion of the fuel fed to the fuel cell to provide heat for upstream endothermic reactions. One method for achieving a VHP with low air pollution is to use these catalytic burners to provide additional heat. If the catalytic burner was chosen to provide the additional heat, its design could change to have a larger catalytic surface area and a more sophisticated heat exchange design. For example, a catalytic burner operated at part load can have a similar but potentially less deleterious air pollutant profile than it had at full-load; less gas reacting at part-load over the same catalytic surface area may allow the gas to react more completely, producing less pollutants, especially after a period of long-term catalyst degradation. The burner's heat exchange efficiency may also change between part and full-load. For example, longer residence times of fluids at part-load can increase the efficiency of heat exchange. A full discussion of methods for achieving a rapidly VHP is available in this Colella (2002(b)). The reader can think of a FCS as being able to achieve a VHP by operating some of its pre-existing equipment as an auxiliary boiler or furnace.

Thermal demand changes much less quickly than electrical demand, for example, in terms of units of energy required by a building per second. As a result, burners within FCSs can be designed to supply heat quickly enough to respond to the rate of change of thermal demand within a building, without thermal storage. Consequently, no thermal storage is assumed in this analysis, although it can be done economically in a decentralized way, for example, by using a building's thermal mass for heat storage.

1.5.5. Impediments to Thermal Networks

Thermal networking is common on university and corporate campuses in the U.S. It is common in many European towns, where the town often owns a district heating network or operates a local utility that serves the town. Thermal networking is extremely realistic for district heating networks that have already been built.

The use of thermal networks is attenuated by several factors. A primary impediment to thermal networking is the high fixed costs of initially installing a network; this investment is profitable but over a longer payback time than the time-horizon desired by many investors (a few years instead of the desired 1-3 years.) A second challenge to networking distributed generators is the vested interests of some large power plant manufacturers and operators. A third challenge is the existence of a coordinating body to own and operate the generators to ensure they work in concert together. A fourth challenge is that some neighbors may not want to cooperate with each other. While American society tends to value individuals maximizing their own benefits, European societies tend to value maximizing the benefits of an entire community, operating in concert. A fifth challenge can be legal restrictions that discourage or prohibit cooperation. A sixth challenge can be an asymmetry of information about the energy demand requirements of surrounding buildings in an area. A seventh challenge can be a dearth of technical knowledge regarding design, construction, and operation of district heating networks. The *MERESS* model can be deployed to begin to address many of these impediments.

The construction of these networks is not strongly limited by technical hurdles. Heat losses from these networks are primarily a function of outside temperature. Colder climates have a greater demand for reusing waste heat from power plants. However, heat losses from networks in colder climates may be greater unless the pipes are more highly insulated.

1.5.6. MERESS Model Focus

The *MERESS* model focuses on a campus setting, because many of these impediments mentioned above are mitigated in this setting. For example, campuses run by colleges, corporations, or governments generally can tolerate higher fixed cost investments with longer financial paybacks. Within a campus setting, buildings are collectively owned, and therefore they are more likely to have coordinating bodies, incentives to cooperate, and an intention to maximize benefits to the campus community. Because campuses can own their own utility lines, they face few legal restrictions to networking. Since buildings are collectively owned, campuses can avoid asymmetries of information in different buildings' energy needs. For these reasons, the *MERESS* model focuses on a campus setting.

1.6. Project Objectives

The goal of this project is to develop a simulation tool to evaluate the electricity and heat supplied by networks of FCSs against real-time electricity and heating demand in California buildings. The objectives of the project were:

1) Evaluate GHG emission reductions in five main types of California buildings with the use of FCSs, so as to determine the most suitable building types for implementation.

2) Evaluate GHG emission reductions with different network configurations characteristic for California (stand alone, electrically and thermally networked), so as to determine the most suitable network designs.
3) Identify potential policy options available to California for encouraging the design of distributed energy networks that reduce GHG emissions.

To provide an even more comprehensive modeling tool and analysis, and to address reviewer suggestions in response to the original proposal, the research team expanded the original Project Objectives to include these additional objectives:

4) Analyze GHG reductions in the context of costs,
5) Evaluate an even larger array of building types and network configurations, and
6) Develop recommendations for policy makers, FCS manufacturers, building owners, and GHG inventory developers on how to best meet state-mandated GHG reduction targets using FCSs, with the greatest long-term environmental benefit for each dollar spent.

In combining these six Project Objectives, the phrase "the most suitable" above came to refer to either the installations with the lowest total electricity and heating costs (including the fixed and variable costs of resources and fuel over the investment time horizon), or the installations with the lowest GHG emissions. "The most suitable" installations were also evaluated from the point-of-view of FCS manufacturers; installations were indentified that would lead to the highest FCS installed capacity, and therefore the highest sales revenue to FCS makers.

For reference, the five main types of buildings investigated were offices/classrooms, museums/libraries, residences, wet laboratories, and dry laboratories. (Wet laboratories are buildings designed to handle multiple experimental set-ups involving chemicals, drugs, biological matter, and/or electronics, which require specialized piped utilities, direct ventilation, exhaust fume extractors, workbenches designed for noxious fumes, dust control, and/or temperature-and humidity-sensitive heating, ventilating, and air-conditioning (HVAC) systems. They include biology and chemistry labs. By contrast, dry laboratories are buildings that primarily handle materials, electronic equipment, or large instruments that require a dry environment. They may require specialized equipment such as high performance HVAC, exhaust fume extractors, vibration control, and/or dust control. Examples include computing facilities, robotics labs, and clean rooms.)

1.7. Report Organization

Stemming from these Project Objectives, the results are discussed in different sub-sections of the *Results*. Project Objective (1) results are primarily discussed in these *Results* sub-sections:

- Sub-section 3.3 *Scenario B-2 – Maximizing Savings by Building Type and Load* on page 49, and
- Sub-section 3.8 *Scenario E-2 – Building Types for Maximizing CO2 Reductions* on page 56.

Results related to Project Objective (2) are primarily discussed in six other *Results* sub-sections:

- Sub-section 3.1 *Scenario A – No State or Federal Incentives, No Carbon Tax* on page 47,
- Sub-section 3.2 *Scenario B-1 – Full State and Federal Incentives, No Carbon Tax* on page 48,

- Sub-section 3.4 *Scenario C – Full Government Incentives, $20/tonne CO2 Tax* on page 52,
- Sub-section 3.5 *Scenario D – Full Government Incentives, $100/tonne CO2 Tax* on page 52,
- Sub-section 3.6 *Summary Trends Based on Scenarios B, C, and D* on page 53,
- Sub-section 3.7 *Scenario E-1: Strategies for Maximizing Reductions in CO2* on page 55,

Project Objective (3) recommendations are primarily discussed in the last *Results* sub-section:

- Sub-section 3.9 Identification of Policy Options on page 59, and

in the *Conclusions and Recommendations* chapter. Results related to Project Objectives (4) and (5) are discussed throughout the *Results* chapter. Project Objective (6) results are discussed throughout the *Results* and *Conclusions and Recommendations* chapters.

2.0 Methods: The Optimization Model *MERESS*

An optimization tool, referred to as the Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*), was developed and deployed here to identify FCS configurations with the greatest reductions in GHG emissions and the highest financial savings. *MERESS* allows a user to optimize the configuration of CHP FCSs in supplying heat and electricity to California buildings for maximum financial savings and reductions in GHG emissions. *MERESS* allows a user to evaluate the electricity and heat supply from FCSs in different configurations against competing generators and against the electricity and heat demand from California buildings. *MERESS* can be used to evaluate the feasibility of FCSs in any location in California, given specific information about the buildings in that location, for any set of building load curves, and by any building owner, community, FCS operator, or energy service provider. The research team applies *MERESS* to optimize the configuration of FCSs for a hypothetical town resembling a campus for a college, corporation, or government entity entity, called Campustown, California.

2.1. Installation and Operating Strategies Evaluated

Three sets of unique FCS design options are explained in the *Introduction* under the Sub-section 1.5*: Game-Changing Designs for Installing* on page 25. The 3 sets of design options can be combined into 12 different installation and operating strategies. Of these 12 possible strategies, 5 of these are incorporated into the *MERESS* model. These 5 strategies are tested against a base case in which no FCSs are installed, and heat and power are provided exclusively by a competing generator or set of competing generators defined by the MERESS model's user:

- Base Case: no fuel cells; competing generator defined by user
- Strategy I: Electrically and Thermally Networked (NW), Electricity Power Load Following (ELF), Variable Heat-to-Power Ratio (VHP) , or [NW, ELF, VHP]
- Strategy II: NW, Heat Load Following (HLF), VHP, or [NW, HLF, VHP]
- Strategy III: NW, No Load Following (NLF), Fixed Heat-to-Power Ratio (FHP), or [NW, NLF, FHP]
- Strategy IV: Neither Electrically Nor Thermally NW but rather Stand Alone operation (SA), HLF, VHP, or [SA, HLF, VHP]
- Strategy V: SA, NLF, FHP, or [SA, NLF, FHP]

Table 2 summarizes these operating strategies. The model is designed to investigate these five strategies because they are unique. Fuel cell manufacturers have not typically designed these features (such as VHP) and these control strategies (such as HLF) into their commercially-available systems. They also typically have not installed systems to be both thermally and electrically NW. Most manufacturers build and install their systems to be SA, NLF, with a FHP, or according to Strategy V above. In this way, Strategy V acts as a benchmark of status quo designs against which to compare the performance of other strategies. A primary goal of the *MERESS* model is to use relatively inexpensive simulation studies to identify more financially and environmentally effective ways to design and install FCSs. For this reason, *MERESS* is a system-wide model of an entire energy network composed of FCSs and competing generator(s).

Strategy	Electrically and Thermally Networked (NW) or Stand Alone (SA)?	Electricity Power Load Following (ELF), Heat Load Following (HLF), or No Load Following (NLF) ?	Variable Heat-to-Power Ratio (VHP) or Fixed Heat-to-Power Ratio (FHP)?
I	NW	ELF	VHP
II	NW	HLF	VHP
III	NW	NLF	FHP
IV	SA	HLF	VHP
V	SA	NLF	FHP

Table 2. Operating strategies investigated

2.2. Model Capabilities

Given a certain installation strategy (I through V), *MERESS* finds the optimal capacity installation of FCSs to achieve the highest financial savings for the town of Campustown, California, given a desired GHG emission tax rate and the particular electricity and heating demand characteristics of the town's buildings. *MERESS* also identifies strategies that maximize reductions in CO_2 emissions, for a given set of user specified inputs. Users can use *MERESS* to find these strategies for maximizing CO_2 emission reductions through scenario analyses with an extremely high, unrealistic carbon tax. For scenarios in which FCSs operate SA (Strategies IV and V), *MERESS* also finds the most economical buildings for installation, and the particular buildings that will achieve the highest reductions in CO_2 emissions.

MERESS focuses both on cost and emission reductions, and not emission reductions alone, so as to have a better grounding in reality, and so as to be more useful to fuel cell developers and building owners who inevitably must trade-off environmental concerns at a price.

Unlike many models that describe power plants, *MERESS* is a demand-pull model (not a supply push model). The quantities of electricity and heat demanded by users influence the FCS' rate of consumption of upstream consumable materials, such as fuel, its internal fluid flow rates, and its electricity and thermal output rates. The *MERESS* model aims to increase the match between both the heat and power supplied by the FCSs and the heat and power demanded by the buildings the FCSs serve. The *MERESS* model does this under the constraints of costs and the operating capabilities of the FCSs, as specified by the model's user.

2.3. Optimization Function

MERESS finds the optimal capacity installation of FCSs to achieve the highest financial savings for Campustown, California. The base case is a case without any FCSs. Savings are calculated relative to this base case, which is constant for any set of model runs. In this base case, a competing generator or set of competing generators provide all electricity and heat to Campustown, California. *MERESS* allows the user to specify the competing generator's financial and operational characteristics. The optimization (goal or objective) function maximizes savings for the case with fuel cell installations (Case A) relative to a case with none installed (the base case). In its most basic form, the goal of *MERESS* is to maximize savings (S), defined as

$$S = C_A - C_B, \text{ where}$$

where C_B is the total cost of all electricity and heat for Campustown for the base case with no FCSs installed, and C_A is the total cost of all electricity and heat for Campustown under Case A with a certain installed capacity (i) of FCSs. The decision variable for the optimization is the number of FCSs installed, or the installed capacity (i). C_A and C_B are functions of the electricity demand (D_E) and heating demand (D_H) from each building in Campustown at every hour over the course of one year. C_A is a function of i. C_A is also defined as

$$C_A = F_A + G_A, \text{ where}$$

F_A is the total costs of electricity and heat from the FCSs, including FCS installation and maintenance costs, and natural gas fueling costs, and G_A is the total costs of electricity and heat from the competing generator in the case in which some FCSs are installed and this generator supplies only a portion of the total electricity and heat demanded. Because C_B represents the base case, its value must remain constant for any set of model runs. Please note that the above optimization function for maximizing savings (S), where $S = C_A - C_B$, produces the same results as minimizing costs with FCS (C_A), as long as C_B is constant, which it is. The optimization function could be defined in either way. Either way it produces the same results. Microsoft Excel Solver was used to obtain solutions to resulting non-linear optimization problems and to make the *MERESS* model accessible to a wide range of users.

2.4. Input Data

2.4.1. Electricity and Heating Demand Load Curves for Buildings

MERESS allows the user to input electricity and heating demand curves from buildings. In this way, the user can evaluate the benefits of installing systems in the buildings that the user cares about. The user can specify electricity and heating demand data at hourly time steps for an entire year. Alternatively, the user can rely on demand data for buildings already available in *MERESS*.

For the results presented in this report, *MERESS* models the electricity and heating demand curves for buildings Campustown, California after buildings on the Stanford campus. Stanford building demand data are available for free, for a large number of buildings, at precise time increments (one hour), over the course of one year. Although the original project proposal suggested only investigating demand curves for five buildings, this study investigated a much larger number. All 300+ campus buildings are simulated based on a representative sample of 30 buildings. According to statistical guidelines, an underlying population can be reasonably represented by a sample population of 30 or more (Devore 1995). (As a general rule of thumb, if the sample size is greater than 30, the standard deviation of the sample can be replaced with that of the underlying population, and the mean of the sample is consistently within rounding of the population mean.) The sample population of 30 buildings is composed of five different building types. These five building types generally can represent all of the buildings on the entire campus. The measured data for electricity and heat demand from the sample population of 30 buildings are scaled up in proportion to the building's representation in the energy area, to represent electricity and heating demand throughout the entire town. Yearly data are simulated by using four sample weeks of measured data, from each of the four seasons, to include the effect of seasonal variations. **Figures 5** and **6** show examples of some of the sample input data for building load curves for one week during winter from five buildings of five different types, for electricity and heating demand, respectively. The five main types of buildings investigated were offices/classrooms, museums/libraries, residences, wet laboratories, and dry laboratories. Wet laboratories are buildings designed to handle multiple experimental set-ups involving chemicals, drugs, biological matter, and/or electronics, which require specialized piped utilities, direct ventilation, exhaust fume extractors, workbenches designed for noxious fumes, dust control, and/or temperature-and humidity-sensitive heating, ventilating, and air-conditioning (HVAC) systems. They include biology and chemistry labs. By contrast, dry laboratories are buildings that primarily handle materials, electronic equipment, or large instruments that require a dry environment. They may require specialized equipment such as high performance HVAC, exhaust fume extractors, vibration control, and/or dust control. Examples include computing facilities, robotics labs, and clean rooms. In this way, electricity demand (D_E) and heating demand (D_H) are simulated for each building in Campustown at every hour over the course of one year. (The available thermal building demand data did not include the temperatures at which heat was demanded; as a result, an analysis of second law constraints was beyond the scope of this analysis.)

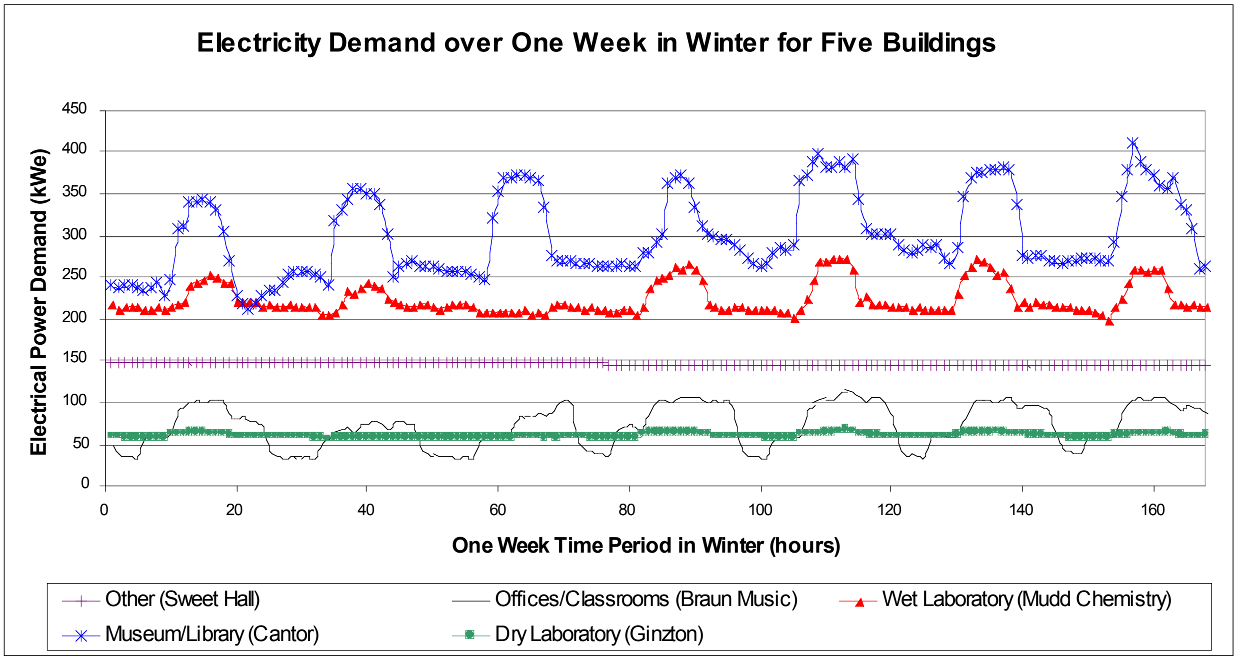


Figure 14. Sample measured input data for building load curves showing electricity demand from five different building types over one representative week during winter

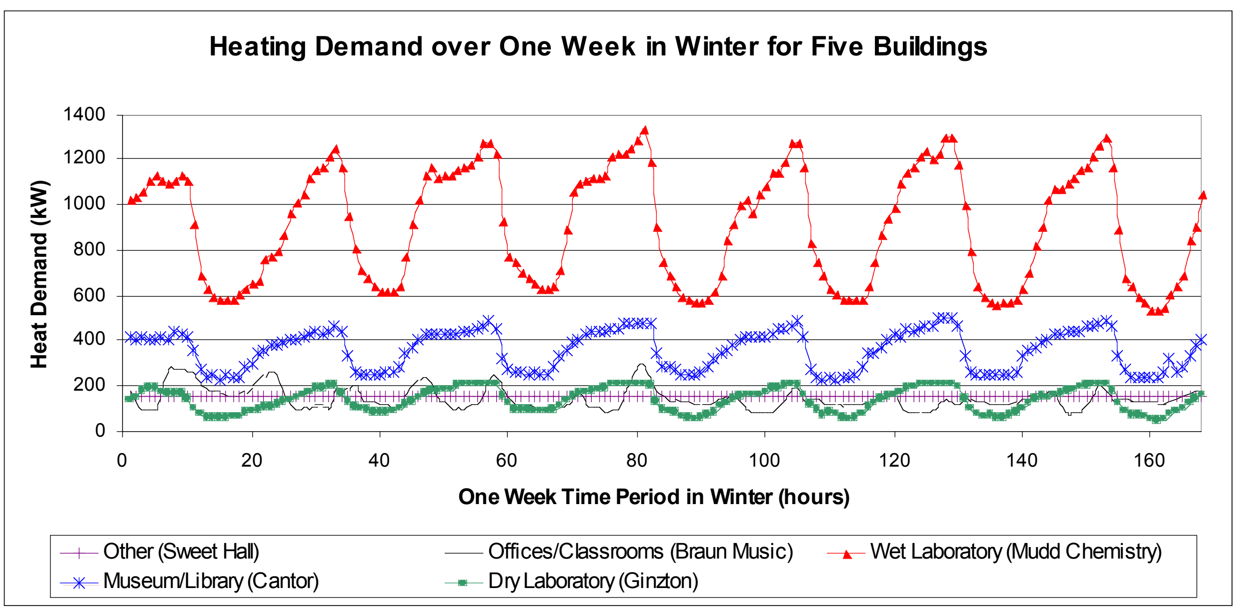


Figure 15. Sample measured input data for building load curves showing heating demand from five different building types over one representative week during winter

2.4.2. Cooling Demand Load Curves

MERESS does not analyze cooling demand, separated out from electricity demand, for three main reasons. First of all, an analysis of cooling demand, specifically, as separated out from electricity demand, is outside the contracted project scope. The original project proposal and objectives did not include an analysis of cooling demand. Second of all, to be practical for a greater quantity of users, the *MERESS* model does not specifically separate out cooling demand as a sub-segment of electricity demand. Most cooling in California is done through air conditioning and fans, which show up as a portion of the electrical load. Most building owners do not measure their cooling demand over time, or the portion of their electrical load due to cooling over time. As a result, although studies exist that have established cooling demand prediction methods, measured cooling demand data from building owners is often not available (Proctor et al. 1995). For the MERESS model to be useful to a greater number of building owners, the data input requirements were limited to data sets of electricity and heating consumption that are more likely to be measured by building owners. Third of all, distributed FCSs that provide cooling power are technically still under prototype development. They are still a few years away from being commercially available. By contrast, the focus of this work was to evaluate semi-commercial FCS and to suggest design improvements to make them more economical and environmentally-impactful. As a result, this initial version of the *MERESS* model does not evaluate cooling demand load curves separately from electricity load curves.

2.4.3. FCS Operating Data

MERESS allows the user to model the FCS of their choice. The user can input a particular FCS's operating and financial data. In this way, the user can evaluate the benefits of installing a particular system that they care about. Alternatively, the user can rely on the FCS operating and financial data already available in *MERESS*.

For the results presented in this report, *MERESS* models a PAFC system in preference to other fuel cell types because environmental analyses show that lower temperature systems (PAFC and PEMFC), which have lower electrical efficiencies, can only achieve reductions in GHG emissions through CHP and effective heat recovery that is genuinely needed and consumed in buildings. *MERESS* models the PAFC system by United Technologies Inc., brand-named the PureCell, which has a maximum electrical output of 200 kWe and maximum thermal output of 264 kW of heat, under normal operating conditions (UTC Fuel Cells 2001; UTC Fuel Cells 2003). *MERESS* models the PureCell over other fuel cells because it is one of the only commercially sold stationary FCSs operating on natural gas, its operating and financial data are publicly available, and this system has been technically proven over a 20+ year period during which time 300+ operating prototype and semi-commercial systems have been deployed throughout the world. Also, in contrast to other fuel cell types and systems, the PureCell has been engineered to quickly change its electrical output in response to changes in electrical demand. No other American-made FCS has been as extensively deployed or as technically proven. For example, the other major U.S. stationary FCS manufacturer, Fuel Cell Energy, sells a stationary MCFC system that has an average lifetime of only two to three years. Two other companies, Bloom Energy (formerly Ion America) and Siemens-Westinghouse, are developing stationary SOFC systems, but they have not yet sold any, and they do not disclose their FCS's operating and financial data to the public. However, fuel cell manufacturers can use *MERESS* to determine the environmental and financial impact of their systems within buildings and entire energy areas, which their current models do not do.

MERESS models the PureCell between an electrical operating range of 100 to 200 kWe. Under conventional operating conditions, over this range, the PureCell has a FHP of about 1.3, as shown in **Figure 13**, and, consequently, a constant net system electrical efficiency and constant heat recovery efficiency. However, *MERESS* enables the system to be modeled under unconventional operating conditions, in which it can achieve a VHP, and can vary its effective electrical and heat recovery efficiencies. *MERESS* allows the user to specify a representative heat-to-power ratio range.

For the results presented later in this report, **Table 3** shows a set of representative operating data for the FCSs modeled in *MERESS*. The system operates with a net electrical efficiency of 37%, a heat recovery efficiency of 48%, for a combined electrical and thermal (overall) efficiency of 85% (37% + 48% = 85%). These efficiencies are representative for PAFC. They are based on efficiency data from the only U.S. commercial supplier of stationary PAFC, United Technologies Inc. (UTC Fuel Cells 2001; UTC Fuel Cells 2003). *MERESS* allows the system to be operated outside of these conditions, with an intentionally lower electrical efficiency, under variable heat-to-power strategies. With a VHP, the system is sometimes intentionally operated with a lower net system electrical efficiency, so as to supply additional heat that is demanded. *MERESS* can explore the heat-to-power ratio over a full spectrum of part-load operations. For example, for the results presented here, the heat-to-power ratio range is chosen to range from 1.3 to 2.5 in these variable heat-to-power scenarios. A maximum heat-to-power ratio of 2.5 for a 200 kWe system translates to a maximum thermal output of 500 kW per system. For these scenarios, *MERESS* assumes the efficiency of this marginal heating is 90%. Users can conduct sensitivity analyses with *MERESS* to investigate how their results change if the FCSs have different electrical and heat recovery efficiencies.

Fuel Cell System Operating Data	Quantity	Units
Maximum Electrical Output	200	kw
Minimum Electrical Output	100	kw
Maximum Heat-to-Electric Power Ratio	2.5	
Minimum Heat-to-Electric Power Ratio	1.3	
Baseline Heat-to-Electric Power Ratio for Fixed Heat-to-Power Ratio Operation	1.3	
Natural Gas Fuel Consumption (in Units of Energy) Per Unit of Electric Power Output	9,222	BTU natural gas/ kwh of electricity
Marginal Increase in Natural Gas Fuel Consumption (in Units of Energy) Per Unit of Additional Heat Demanded (Variable Heat to Power Ratio Scenarios Only)	3,791	BTU natural gas/ kwh of electricity
Baseline System Electrical Efficiency	37%	
Baseline System Heat Recovery Efficiency	48%	
Baseline System Heat Losses (Percent)	15%	
Baseline System Combined Electrical and Heat Recovery Efficiency	85%	
Heat Recovery Efficiency of Burner-Heater for Marginal Heating (Variable Heat to Power Ratio Scenarios Only)	90%	

Table 3. Model input data for FCS operation

As shown in **Table 3**, the user can model a FCS by choosing several variables in *MERESS*. For example, the user can define both the electrical and heat recovery efficiencies of the system, over a specified operating range. The user can vary the range of minimum and maximum electrical output associated with these efficiency values. Efficiencies can be entered as point values over this operating range. According to the stationary FCS manufacturing data made available to the authors, all of these systems sold in the U.S. exhibit an essentially constant electrical efficiency over their recommended operating range. As a result, to remain consistent with these data, the authors chose to model FCS efficiencies as point values.

There may be some confusion here because an individual fuel cell (without the surrounding balance of plant for fuel and oxidant delivery, etc.) exhibits an electrical efficiency that declines as the electric power output increases, often depicted by a polarization curve. By contrast, a fuel cell system does not exhibit this characteristic. This point has been greatly misunderstood even within the fuel cell industry and even by researchers making policy recommendations about fuel cells. For an illustration of this point, please see O'Hayre et al., Chapter 10, Figure 15.4, p. 287 (2006), which compares a typical fuel cell/fuel cell stack polarization curve with the electrical efficiency curve of a fuel cell sub-system. Based on the data available for stationary fuel cell systems, the authors determined it would be accurate to model the fuel cell systems' electrical efficiency as a point value over their recommended operating range. (As a result of this choice in model design, it is possible to apply the model to other types of distributed generators other than FCSs.)

The electrical and heat recovery efficiencies remain constant for scenarios in which systems are operated with a FHP. By contrast, when the systems are operated with a VHP, their effective electrical and heat recovery efficiencies change. In these scenarios, the system electrical and thermal efficiencies change with the VHP during the course of operation, in response to changes in demand. In the VHP scenarios, the FCS systems can operate at lower effective electrical efficiencies than those specified as point values. In these VHP scenarios, they can operate at higher heat recovery efficiencies.

MERESS considers first law constraints (conservation of energy), but not second law constraints (direction of heat flow from hot to cold) directly in detail. With the UTC systems, the heat recovery temperatures are high enough that most building applications can be met. For example, previous studies by Colella (2003) showed that even lower temperature PEMFC could supply all of their waste heat as recoverable heat to buildings, so long as pinch point analysis and careful heat exchanger design are employed. Since the PAFC operate at higher temperatures than PEMFC, the buildings analyzed in this study can recover their heat more easily. Furthermore, a more detailed analysis including second law constraints was beyond the scope of this work because such building thermal demand data indicating temperatures at which heat is demanded were not readily available.

The systems are assumed to have a lifetime of 10 years (in the field, they have lasted 20 years). The FCS fixed costs, natural gas price, and CO2 mitigation costs are explained in the next sections.

2.4.4. FCS Financial Data

The total yearly fixed costs of the FCSs are calculated from the capital, installation, maintenance, and other costs. **Table 4** shows a *MERESS* table of data inputs for these costs (second column) (Menar 2003; Coletto 2007). The third column lists the annuity payment equivalent of this fixed cost in the second column, assuming a FCS lifetime of 10 years, and based on the annuity formula:

$$A = Pr/(1-1/(1+r)^n),$$

where A is the value of the annuity, P is the principle (the amount borrowed or credited at time t=0), r is the cost of capital, and n is number of years (10 years) over which the annualized payments are made (Ross et al. 2007; Brealey et al. 2007). In this example, r =7.42% to reflect the relatively low borrowing rates that educational institutions access, close to the risk-free rate or government bond rate. (The bond rate was 4.91% on a 30 year bond on Oct. 15th 2007 (U.S. Department of the Treasury 2007)). The sum of these annuity payments in the third column is shown in the total yearly fixed costs of the FCS, shown in the last row ($138,368 in this example). The capital costs ($950,000) are for a single 200 kWe system. The installation costs ($ 250,000) assume ground-level installation, close to utility tie-in lines (such as the natural gas line, city water, and the electricity distribution grid), and close to the building for thermal tie in to the building. The installation and commissioning is turn-key, and includes site design and engineering, all required permits (utility, construction, city, air permits, etc.), and all material and labor. The shipping cost ($20,000) assumes the cost of shipping the system from the manufacturing site in Connecticut to the West Coast. The premium full service contract covers maintenance and repair for 10 years. It is an annual payment of approximately $60,000 for 10 years. It includes preventative maintenance and repairs (labor and parts), scheduled and un-scheduled maintenance, 24/7 remote monitoring, next-day business response to unplanned events, and includes an extended warranty for replacement costs of the major fuel cell components.

The *MERESS* model represents FCS availability and capacity utilization in a representative manner. Availability is defined as the percentage of the time the system is available for use and not shut down for scheduled or unscheduled maintenance. United Technologies Inc. states that the PureCell's previous models have achieved a measured availability in the field of 96% for systems serviced under their company's maintenance contract (Peszko 2007). For simplicity, the *MERESS* model assumes the FCS availability is 100%, although the user can change this value in the code. While availability is an input term, capacity utilization is an output term. Please note that the term availability conveys a different concept than the term capacity utilization. Capacity utilization, or load factor, is defined as the percentage of the time a power plant is operating at its rated maximum power (its maximum capacity), and is a primary determinant of the costs of energy delivered. The capacity utilization of FCS changes for any model run and is an output variable of the model. Typically, the *MERESS* model's optimized results are correlated with a high FCS capacity utilization.

The *MERESS* model represents the system lifetime in a financially accurate manner. The model assumes a FCS resale or scrap value at the end of 10 years of zero, which is probably an under-estimate. Systems have lasted much longer than 10 years, and, for broken systems no longer under warranty, their spare parts could be sold. According to UTC, the warranty would cover the cost of replacement of any FCS components, including the fuel cell stack, over the 10 year period of the warranty (Peszko 2007). Although in the past UTC recommended fuel cell stack replacement every 5 years and fuel reformer replacement every 7 years, UTC now estimates that its new generation of stacks will last 10 years (Menar 2003; Colella et al. 2005 (b); Peszko 2007). The extended warranty, chosen for the analysis here, includes stack and reformer replacement costs (Peszko 2007). The currently unavailable features of FCSs such as VHP are assumed to add no additional cost.

Fuel Cell System Costs -- Fixed Cost per year	Amount Borrowed (or Credited) at Time t = zero [P] ($)	Annuity [A] ($)
Capital Costs of 200 kW Fuel Cell System	$ 950,000	$137,869
Installation Costs	$ 250,000	$ 36,281
Commissioning Costs (Start-up, Testing, Tutorials for Operators)	$ 20,000	$ 2,903
Shipping	$ 20,000	$ 2,903
Premium Service Contract (Maintenance and Replacement) -- Annuity Payments		$ 60,000
Fuel Cell System Incentives -- Federal and State		
California Self-Generation Incentive Program (CA SGIP) at $2500/kWe	$ 500,000	$ 72,563
Federal Investment Tax Credit (FITC) at $1000/kWe	$ 200,000	$ 29,025
Fuel Cell System Fixed Costs -- Total Yearly Fixed Costs		**$138,368**

Table 4. Model input data for FCS costs

2.4.5. Government Incentives

Three government incentives are also included in the model. First, the state of California subsidizes FCSs through the SGIP at a rate of about $2,500/kWe.[3] This incentive is shown in **Table 4**. Second, the federal government provides a Federal Investment Tax Credit (FITC) up to $1000/kWe or 30% of the net investment cost, whichever is less.[4] This incentive is also shown in **Table 4**. Third, the state of California subsidizes small scale natural gas CHP at a rate of about $1.50 /million BTU. In the model, this subsidy is subtracted from the market price for natural gas in California, which is $8.95/million BTU on average in 2006 (EIA 2007). The natural gas price seen by the FCSs is this California natural gas rate minus this state subsidy.

2.4.6. Carbon Tax

The Intergovernmental Panel on Climate Change (IPCC) evaluates the global warming mitigation cost of CO_2 over a range of between $20 and $100/tonne CO_2 (Working Group III IPCC 2007). This study adopts a carbon tax over the same range. The carbon tax increases the natural gas price seen by the FCSs. It also increases the electricity and heating price of the competing generator.[5]

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[3] See http://www.pge.com/selfgen/ for restrictions. If the new plant replaces existing CHP, the incentive may not apply.

[4] For tax paying entities. See the U.S. Energy Policy Act of 2005.

[5] On top of a carbon tax, the model does not also financially credit generators for avoided emissions through an emission trading system. Most regions that try to internalize the external costs of GHG emissions choose between either a carbon tax or an emission trading system, not both. Although an emission trading system does not preclude the use of carbon taxes, the two are often seen as competing policy instruments aimed at the same goal of GHG emission reductions.

For the results shown in this report, the carbon tax was assumed to have the same effect on increasing electricity and steam heating prices of the competing generator that a market-related increase in fuel price might have. In the model, the tax increases the price of electricity and the price of steam in proportion to the relative fuel consumption associated with each. This approach is an accepted marginal cost accounting method (Atkinson et al. 2006). This method is also chosen because it most closely reflects the use of carbon within the energy system, and, therefore, is the most appropriate set of assumptions for the CO_2 calculations presented in the results section in *Scenario E-1: Strategies for Maximizing Reductions in CO2* and *Scenario E-2 – Building Types for Maximizing CO2 Reductions* on page 56.

MERESS allows the user to change the portion of the carbon tax associated with steam or electricity, so as to better reflect the competitive behavior of the competing generators that the user wants to model. In practice, competing generators can choose to impart the effect of the carbon tax onto consumers in different ways, and can change these methods over time. For example, when fuel costs increase because of a carbon tax or any other reason, competing generators may tend to pass on this increase to the portion of its consumer base that has less bargaining power and less access to competition, sometimes called captured consumers.

In the market modeled here, the energy area may be considered more of a captured consumer in its purchase of steam heating than in its purchase of electricity, because a less competitive market exists for steam heating generation than for electricity. Under these circumstances, a competing generator may pass on a fuel price increase more to the steam heating price than to the electricity price. Indeed, as fuel prices have risen, General Electric (GE), which owns the CHP CCGT plant on the campus, has increased the steam heating price more than the electricity price in its contract with Stanford. These observations apply to the Stanford case, and may also apply to other campus settings with similar market structures.

The method that a competing generator chooses to recuperate the effect of a carbon tax can significantly impact the most viable installation strategy (Strategies I-V) for FCSs. If a competing generator chooses to associate the tax entirely with electricity price, the most economic strategy for installing FCSs is completely different than if the competing generator associated the tax entirely with steam price, or some combination of these. This unknown and potentially variable pricing behavior increases investment risk for the competing generator's competitors.

The effect of a carbon tax increasing is analogous to the effect of fuel prices increasing in many cases. A user can change the same input parameters in the *MERESS* model not only to evaluate an increase in carbon tax, but also to evaluate an increase in fuel prices. Users can use *MERESS* to evaluate the effect of fuel costs trending upward, as projections from the U.S. Department of Energy's (DOE) Energy Information Administration (EIA) or the CEC might suggest.

2.4.7. Competing Generator Data

The *MERESS* model tests the 5 strategies against a base case in which no FCSs are installed, and heat and power are provided exclusively by a competing generator or set of competing generators defined by the *MERESS* model's user. For these results presented, the base case competing generator is a high-performance CHP CCGT power plant. *MERESS* allows the user to specify the competing generator's financial and operational characteristics. For the scenario results presented in this report, the competing generator was assumed to be a CHP CCGT power plant modeled after the same plant installed on the Stanford campus. The generator is assumed to be available to provide electricity or heat not provided by the FCSs. Like the Stanford plant, it can also sell excess electricity over the high-voltage transmission grid. In this way, this competing generator mimics the financial situation of the Stanford cogeneration plant, and the model reflects the financial situation encountered by many corporate and university campuses that chose to buy power from a nearby cogeneration plant, or another source. Incorporating competing generator data into the model in this way also allows some modeling of emergent competitive behavior; in response to changes in competitor behavior (efficiency, prices, allocation of taxes, etc.), the best strategies (from Strategies I through V and more) for building owners to implement for maximizing carbon emission reductions and economics will change (Axelrod 1997.)

Competing Generator: Natural Gas Combined Cycle Gas Turbine Plant		
Cost of steam for heating	0.056	\$/kWh steam
Cost of electricity	0.085	\$/kWh electricity
Baseline System Heat Recovery Efficiency	0.22	
Baseline System Electrical Efficiency	0.40	
Baseline System Heat Losses	0.38	

Table 5. Model input data for competing generators

The competing generator data are based on financial and efficiency data for the Stanford 50 megawatt (MW) cogenerative power plant, shown in **Table 5** (Stanford Utilities 2007). The steam price above is \$0.056/kWh of steam (\$16.32/million BTU of steam) and the electricity price is \$0.085/kWh of electricity. These values are the estimated prices of steam and electricity at the University excluding the cost of the distribution networks. Specifically, in both cases, the cost of the distribution network is estimated from Utilities department data and subtracted from the price the University charges to its departments for steam and electricity, respectively. This adjustment enables apples-to-apples comparisons between the fuel cell and competing generator scenarios. (Another approach to make a fair comparison is to add the estimated cost of the distribution networks to the fuel cell scenarios.) Further details of this calculation are shown in Appendix D. *MERESS* is equally capable of modeling retrofits as it is of modeling new installations, simply by accounting for the difference in costs in these two approaches, which the user can input.

In the analysis shown, the authors wanted to accurately model the choices that a town makes when it decides either 1) to buy electricity and heat from a dedicated distributed gas turbine generator, or 2) to install and operate a network of distributed fuel cell systems. In making this choice, the town experiences neither energy nor demand charges. These charges are leveled by external utilities. The town only sees the capital and running costs of the FCS, and the CCGT's electricity and steam prices. The *MERESS* financial model represents this set of choices between two competing financial decisions accurately.

MERESS models the financial decisions from the point-of-view of the town. It does not model the financial decisions that the competing generator's owner makes directly. As the FCSs displace competing generator capacity, the competing generator is free to sell this displaced power into the grid. This opportunity is true for the Stanford cogeneration plant, and it typically sells half of its maximum electrical capacity (about 25 MW) over the grid under normal operation. Waste heat associated is associated with this electricity sold. However, these decisions of the competing generator are not directly modeled in *MERESS*. *MERESS* models financial decisions from the viewpoint of the town.

2.4.8. Networking

Within the model, FCSs that are electrically networked can send their electricity to surrounding buildings via the local low-voltage electricity distribution grid, with no energy losses. Systems that are thermally networked can send their heat to surrounding buildings via steam heating pipes with an 8% heat loss. This assumption reflects the measured data describing these networks on the Stanford campus, and many other university and corporate campuses in California. Scenarios modeled with non-networked systems do not include this downstream heat loss because steam is not conveyed over a network. *MERESS* treats NW FCSs as both electrically and thermally NW. The electricity and heating distribution lines are owned and were previously installed by Campustown, like many corporate and college campuses. (As a result, the model does not encode any legal interpretations of regulatory restrictions of electrically networking across public roads that could affect installations in other types of environments. At the same time, networked FCSs are assumed to adhere to California Rule 21 electrical interconnect requirements for distributed generators.)

3.0 Results

Simulation results from various models runs of *MERESS* are presented here. The research team first summarizes these results in this sub-section and then discusses these results in detail in subsequent sections. For these results presented, the base case competing generator is a high-performance CHP CCGT plant.

- Scenario A examines the case of no state or federal incentives or a carbon tax. In Scenario A, Strategy I [NW, ELF, VHP] achieves the highest reductions in CO_2 emissions, 29% relative to the base case of no FCSs installed, with a marginal energy cost savings of 3% annually. In this scenario, Strategy I also shows the most installations or sales, 17% of the total average electrical power installed in the geographic area of Campustown, which producers typically associate with profit maximization. Table 7 summarizes these results.

- Scenario B examines the case of full state and federal incentives, but no carbon tax. In Scenario B, Strategy I again achieves the highest annual energy cost savings, 15% relative to the base case, and the highest reduction in CO_2 emissions, 31% relative to the base case. By contrast, Strategy III [NW, NLF, FHP] achieves the highest number of installations, 46% of average electrical power installed. This comparison illustrates a dichotomy between the most economical strategy for building owners and the most economical strategy for fuel cell manufacturers. Under Scenario B, if either Strategies IV or V are implemented, then the most economical installations in both cases are wet laboratory buildings. Table 8 summarizes these results.

- Scenario C examines the case of full state and federal incentives and a \$20/tonne CO_2 tax. In Scenario C, Strategy I again achieves the highest annual energy cost savings, 17% relative to the base case, and the highest reduction in CO_2 emissions, 33% relative to the base case. By contrast, Strategy III again achieves the highest number of installations, 49% of average electrical power installed. Between Scenario B and Scenario C, the results do not change much; a \$0/tonne CO_2 tax has nearly the same effect as a \$20/tonne CO_2 tax. The carbon tax drives up both the FCS and competing generator running costs in a similar manner. Scenario C results are summarized in Table 10.

- Scenario D examines the case of full state and federal incentives and a \$100/tonne CO_2 tax. Scenario D illustrates a scenario in which these three competing goals, 1) cost savings to building owners, 2) GHG emission reductions, and 3) high FCS manufacturer sales revenue, are achieved with three different strategies. The highest annual energy cost savings is achieved with Strategy I, with a 25% savings relative to the base case. The highest reduction in CO_2 emissions is with Strategy V [SA, NLF, FHP], 34% relative to the base case. The most economical strategy for building owners is with Strategy III, with 60% of average electrical power covered by FCSs installed. Table 11 summarizes these results.

- Scenario E examines the case of an unrealistically high carbon tax (\$1,000,000/tonne CO_2) so as to alter the function of the model such that the model optimizes not for the highest financial savings, but rather the highest reduction in CO_2 emissions. The results for Scenario E demonstrate that the strategies that achieve the highest reductions in CO_2

emissions are Strategies I, III, and V. Of these, Strategy V achieves the maximum reduction in CO_2 emissions, although Strategies I and III are not far behind. Among Strategies I, III, and V, Strategy III leads to higher sales for FCS manufacturers. Strategy II leads to the absolute highest FCS sales for fuel cell manufacturers, but the lowest absolute CO_2 emission reductions. Figure 5 summarizes these results. Table 12 summarizes these results.

Table 6 summarizes the key changes in inputs between these five scenarios. Table 6 also summarizes the results of scenario runs by reporting the best strategies for each scenario. Results from the various scenarios are compared visually in Figures 11 and 12, which graph optimal savings and installed capacity against financial incentives.

Input Conditions			Summary Results		
Scenario	Incentives for fuel cells* and for CHP** (N/Y)	Carbon Tax ($/tonne CO_2)	Strategy with Highest Energy Cost Savings	Strategy with Highest CO_2 Savings	Strategy with Highest Sales/ Manufacturer Profit
A	N	0	I	I	I
B	Y	0	I	I	III
C	Y	20	I	I	III
D	Y	100	I	V	III
E	Y	1,000,000	I	V	III

Key Assumptions:

base case = no fuel cells, all CHP combined cycle gas turbine plant

common fuel for fuel cells and turbine = natural gas

base case electricity and heating costs (no fuel cells) = $20 million/yr

cost of capital (r) = 7.42% = educational borrowing rate ≈ bond rate

fuel cell turn-key cost (without incentives) = $6,200/kWe

* fuel cell incentives: $2,500/kWe (state); $1,000/kWe (federal)

free market price of natural gas = $8.95/million BTU

** natural gas price with CHP incentive = $7.45/million BTU

Color code:

yellow = highest energy cost savings

green = highest CO_2 emission reductions

blue = highest sales / fuel cell manufacturer profit

Table 6. Key inputs and results for scenario runs

3.1. Scenario A – No State or Federal Incentives, No Carbon Tax

Simulation results are presented in **Table 7** for the scenario in which no state or federal incentives or carbon tax are applied for installing fuel cell or CHP systems. The base case refers to a scenario in which no FCSs are installed, and heat and power are provided exclusively by the competing generator.

The only strategy that is economical is Strategy I [NW, ELF, VHP] (highlighted in yellow). Campustown, California experiences the lowest heating and electricity costs by installing 16 FCSs, or 3.2 megawatts of electric power (MWe). This electrical capacity is 12% of Campustown, California's peak electrical power needs and 17% of its average electrical power demand that year. Strategy I achieves a savings compared with a scenario in which no FCSs are deployed (the base case). This savings is $800,270 per year, or 3% of the base case costs.

Strategy	Optimal number of fuel cell systems installed	Optimal installed fuel cell system capacity (MWe)	Optimal installed fuel cell system capacity as a percent of peak power (%)	Optimal installed fuel cell system capacity as a percent of average power (%)	Total costs of electricity and heat provision ($/yr)	Total financial savings compared with base case of no fuel cells ($/yr)	Annual cost savings (%)	Total carbon emissions (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (%)
I	16	3.2	12%	17%	$22,106,881	$ 800,270	3%	96,489	-39,863	-29%
II	0	0	0%	0%	$22,907,152	$0	0%	136,352	0	0%
III	0	0	0%	0%	$22,907,152	$0	0%	136,352	0	0%
IV	0	0	0%	0%	$21,037,754	$0	0%	136,352	0	0%
V	0	0	0%	0%	$21,037,754	$0	0%	136,352	0	0%

Table 7. Simulation results for a scenario with no incentives

Strategy I is more economical than the others because the average annual capacity utilization for each FCS's electrical power is 100%, in this simulation run. The average annual capacity utilization for each system's heat recovery is also 100%. In other words, the systems are operating at their maximum output 100% of the time. Therefore, the capital cost of the systems can be recovered more quickly.

Typically, producers associate profit maximization with maximizing sales revenue (although this is not always the case). The profit formula is

$$\text{Profit} = \text{Sales Revenue} - \text{Costs}.$$

Most businesses continually try to increase their sales revenue. They try to do this because they associate higher sales with higher profit. Higher profits are usually associated with higher sales revenue because at higher production levels, costs decline. Costs tend to decline at higher production levels through a variety of mechanisms, such as economies of scale in mass-production. As a result, at higher production levels, the difference between sales revenue and costs (which equals profit) is often higher. For this reason (in part), most businesses continually try to increase their sales within a certain market segment. Similarly, one can expect fuel cell manufacturers to associate profit maximization with the strategy leading to the most sales of FCSs. In this scenario, Strategy I also shows the most installations, 17% of average installed capacity.

Strategy I also achieves a significant reduction in CO_2 emissions, 29% relative to the base case of no FCSs installed. The base case assumes the competing generator supplies all of the electrical power and heating.

Scenario A is the only scenario shown under which all three competing goals are satisfied by the same strategy. Under Scenario A, Strategy I achieves the most financial savings for building owners, the highest sales revenue for fuel cell manufacturers, and the highest reduction in CO_2 emissions. In all other scenarios shown here, the optimal solutions for these competing goals diverge.

Another significant outcome of this scenario run is to demonstrate that just by changing the installation and operating strategy approach to FCSs, they can be installed economically, without any governmental incentives. FCSs have not typically been designed and installed to be connected to thermal networks, to follow electrical loads, and to achieve a VHP, either separately or in concert. This scenario run demonstrates that locations with pre-existing thermal networks (district heating pipes) are excellent retrofit candidates for CHP FCSs.

3.2. Scenario B-1 – Full State and Federal Incentives, No Carbon Tax

Table 8 shows simulation results for the scenario in which full state and federal incentives are applied, but no carbon tax is applied. These incentives were discussed in Section 2.4.5 *Government Incentives* on page 41. The most economical strategy for Campustown, California is again Strategy I [NW, ELF, VHP] (highlighted in yellow), which has an annual energy cost savings of 15%, with FCSs installed at an electrical capacity of 24% of average electrical power. Strategy I also achieves the highest reduction in CO_2 emissions, 31% relative to the base case. By contrast, the most economical strategy for the fuel cell manufacturer is different. As mentioned, producers usually associate profit maximization with maximal sales. The operating strategy that results in the most sales of FCSs is Strategy III [NW, NLF, FHP] (highlighted in green), with 44 systems or 46% of average electrical power installed. Strategy III also achieves the second highest reduction in CO_2 emissions, 27% relative to the base case. However, this strategy results in an annual energy cost savings of only 3% for Campustown. These simulations illustrate a striking dichotomy between the most economical strategy for building owners and the most economical strategy for fuel cell manufacturers, although both achieve significant reductions in CO_2. This financial dichotomy pervades most scenarios.

Strategy	Optimal number of fuel cell systems installed	Optimal installed fuel cell system capacity (MWe)	Optimal installed fuel cell system capacity as a percent of peak power (%)	Optimal installed fuel cell system capacity as a percent of average power (%)	Total costs of electricity and heat provision ($/yr)	Total financial savings compared with base case of no fuel cells ($/yr)	Annual cost savings (%)	Total carbon emissions (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (%)
I	23	4.6	17%	24%	$19,513,975	$3,393,176	15%	93,560	-42,792	-31%
II	36	7.2	27%	38%	$20,882,548	$2,024,604	9%	119,309	-17,043	-12%
III	44	8.8	33%	46%	$22,213,122	$ 694,029	3%	100,215	-36,137	-27%
IV	12	2.4	9%	13%	$20,928,212	$ 109,542	1%	109,739	-26,613	-20%
V	30	6.0	22%	32%	$20,602,946	$ 434,808	2%	101,763	-34,589	-25%

Table 8. Simulation results for a scenario with government incentives

As with Scenario A, in Scenario B, Strategy I is more economical than the others because each FCS's capacity utilization for electrical power and heat recovery is very high at the optimized level of installed FCS capacity that the model selects. For the optimized run results, the systems are operating at close to their maximum output most of the time. At such high capacity utilizations, the capital costs of the FCSs are paid back more quickly and the total electricity and heating costs decline.

A comparison of the results for Scenarios A and B shows that, as the government subsidies for FCSs increase, the optimal installed capacity of the FCSs increases. As the state and federal incentives for purchasing FCSs are augmented from zero to a positive value, these FCSs become relatively more economical than the competing generator. These results are consistent with what one would intuitively expect.

Table 8 also indicates that networking fuel cells thermally and electrically is more economical than not networking them. The NW strategies (I, II, III) all achieve higher savings than the SA strategies (IV, V). Networking has the highest savings most likely due to the resulting load leveling effect. Load leveling increases system capacity utilization.

Table 8 also shows that when there is networking (Strategies I, II and III), fuel cells are more economical if they combine either electrical or thermal load following with a VHP (Strategies I and II). **Table 8** indicates that, for the assumptions of this analysis, when fuel cells are operating SA, they are more economical if they combine NLF with FHP (Strategy V). The *MERESS* model can be extended to test additional configurations, such as synergies with plug-in hybrid vehicles and electrical storage.

Note that the observations in the previous paragraphs do not appear to be generalizable to all scenarios. They depend on the underlying assumptions of the scenario and change with, for example, the relative price of the competing generators steam and electricity.

3.3. Scenario B-2 – Maximizing Savings by Building Type and Load

For FCSs that are operated as SA, the relative economics of installing a system in one building versus another depends on an individual building's electricity and heating demand curves over time. In the case that Strategy IV is implemented, **Table 9** shows the only economical installations, grouped according to building type and by the building name with the most similar load curve to that modeled. The load curve tested for each building is a scaled up version of the load curve of the underlying sample building. Of the 30 building load curves investigated, only 6 are economical, and only marginally; these are wet laboratories and dry laboratories. Of these, the one that is most economical for Campustown is the building load curve most similar to that of the Mudd Chemistry building, a wet laboratory, with a 1.5% savings (highlighted in yellow). The most economical installation for fuel cell manufacturers is in buildings with load curves most similar to either Mudd Chemistry building or the Center for Integrated Systems (CIS), a wet laboratory (highlighted in green). To generalize these results for a larger audience, consider that wet and dry laboratories are similar in their energy requirements to many industrial facilities, which also operate around-the-clock at high energy consumption levels.

In the case that Strategy V is implemented, **Table 9** shows the economical installations, by building type and by the building name with the most similar load curve to that modeled. Of the 30 building load curves investigated, only 12 are marginally economical. Of these, the one that is most economical for Campustown is the load curve most similar to the McCullough building, a dry laboratory, with a 3.5% savings (highlighted in yellow). The most economical installation for fuel cell manufacturers is the load curve most similar to the Center for Integrated Systems (CIS), a wet laboratory (highlighted in green), with 9 systems installed supplying electrical capacity for 9% of average electrical demand. The most common building type among the economical group is the dry laboratory. The remainders span the range of building types, from wet laboratories, to museums/libraries, housing facilities, to offices and classrooms. These results underscore the importance of testing the FCS's performance against the particular load curves of the buildings they may serve, rather than generalizing by building type alone.

Strategy IV: Most Economical Buildings for Installations

Building Type	Load Curve Based on this Building	Optimal Number of Fuel Cell System Installations	Optimal Installed Fuel Cell System Capacity (MWe)	Optimal Installed Fuel Cell System Capacity as a Percentage of Peak Power Demand throughout Energy Area	Optimal Installed Fuel Cell System Capacity as a Percentage of Average Power Demand throughout Energy Area	Total Costs of Electricity and Heat Provision ($/yr)	Total Savings for Electricity and Heat Provision Compared with Base Case of No Fuel Cells ($/yr)	Annual Cost Savings (%)
Wet Lab	Mudd (Seeley G) Chemistry	4	0.8	3%	4%	$ 2,332,020	$ 35,993	1.5%
Dry Lab	McCullough (Jack A.)	1	0.2	1%	1%	$ 892,999	$ 9,245	1.0%
Dry Lab	Mechanical Engineering Research Lab	1	0.2	1%	1%	$ 1,010,933	$ 9,521	0.9%
Wet Lab	Center for Integrated Systems (CIS)	4	0.8	3%	4%	$ 4,769,311	$ 38,190	0.8%
Dry Lab	Gates Computer Science	1	0.2	1%	1%	$ 1,436,260	$ 9,525	0.7%
Wet Lab	Gordon Moore Materials Research	1	0.2	1%	1%	$ 1,591,243	$ 7,067	0.4%

Strategy V: Most Economical Buildings for Installations

Building Type	Load Curve Based on this Building	Optimal Number of Fuel Cell System Installations	Optimal Installed Fuel Cell System Capacity (MWe)	Optimal Installed Fuel Cell System Capacity as a Percentage of Peak Power Demand throughout Energy Area	Optimal Installed Fuel Cell System Capacity as a Percentage of Average Power Demand throughout Energy Area	Total Costs of Electricity and Heat Provision ($/yr)	Total Savings for Electricity and Heat Provision Compared with Base Case of No Fuel Cells ($/yr)	Annual Cost Savings (%)
Dry Lab	McCullough (Jack A.)	2	0.4	1%	2%	$ 870,871	$ 31,373	3.5%
Museum/Library	Cantor Center for Visual Arts	1	0.2	1%	1%	$ 382,020	$ 12,697	3.2%
Dry Lab	Gates Computer Science	3	0.6	2%	3%	$ 1,399,993	$ 45,792	3.2%
Dry Lab	Mechanical Engineering Research Lab	2	0.4	1%	2%	$ 988,151	$ 32,303	3.2%
Wet Lab	Mudd (Seeley G) Chemistry	5	1	4%	5%	$ 2,294,912	$ 73,102	3.1%
Housing	Wilbur Dining Hall	1	0.2	1%	1%	$ 521,439	$ 16,309	3.0%
Wet Lab	Center for Integrated Systems (CIS)	9	1.8	7%	9%	$ 4,672,701	$ 134,800	2.8%
Offices/Classrooms	Packard Electrical Engineering	1	0.2	1%	1%	$ 505,021	$ 13,238	2.6%
Offices/Classrooms	Tresidder	1	0.2	1%	1%	$ 638,652	$ 15,804	2.4%
Dry Lab	Ginzton (Edward L.) Labs & Annex	1	0.2	1%	1%	$ 329,250	$ 8,083	2.4%
Housing	Lagunita Dining	1	0.2	1%	1%	$ 552,605	$ 13,536	2.4%
Dry Lab	Green Earth Sciences	1	0.2	1%	1%	$ 918,965	$ 11,168	1.2%

Table 9. Most economical building load curves with SA installation

3.4. Scenario C – Full Government Incentives, \$20/tonne CO_2 Tax

Strategy	Optimal number of fuel cell systems installed	Optimal installed fuel cell system capacity (MWe)	Optimal installed fuel cell system capacity as a percent of peak power (%)	Optimal installed fuel cell system capacity as a percent of average power (%)	Total costs of electricity and heat provision (\$/yr)	Total financial savings compared with base case of no fuel cells (\$/yr)	Annual cost savings (%)	Total carbon emissions (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (%)
I	27	5.4	20%	28%	\$ 21,127,047	\$4,445,570	17%	93,177	-43,175	-32%
II	42	8.4	31%	44%	\$ 22,568,407	\$3,004,210	12%	117,390	-18,962	-14%
III	47	9.4	35%	49%	\$ 24,129,151	\$1,443,466	6%	98,931	-37,421	-27%
IV	17	3.4	13%	18%	\$ 23,133,574	\$ 416,328	2%	101,650	-34,702	-25%
V	39	7.8	29%	41%	\$ 22,551,864	\$ 998,039	4%	94,749	-41,603	-31%

Table 10. Simulation results with government incentives and \$20/tonne CO_2 carbon tax

Simulation results are shown in **Table 10** for the scenario in which full state and federal incentives are applied, as well as a carbon tax at \$20/tonne CO_2. The most economical strategy for Campustown, California is again Strategy I [NW, ELF, VHP] (highlighted in yellow), which has an annual energy cost savings of 17%, with FCSs installed at a capacity of 28% of average power. Strategy I also achieves the highest reduction in CO_2 emissions, 32% relative to the base case. Strategy V achieves the second highest reduction in CO_2 emissions, 31%. The most economical strategy for the fuel cell manufacturer is Strategy III [NW, NLF, FHP] (highlighted in green), with 47 systems or 49% of average power installed, but an annual energy cost savings of only 6% for Campustown. Strategy III also achieves the third highest reduction in CO_2 emissions, 27%. This example again illustrates the dichotomy between the most economical strategy for building owners and that for fuel cell manufacturers. It also illustrates the trade-off between the most environmentally benign strategy (Strategy I) and the most economical one for fuel cell manufacturers (Strategy III).

3.5. Scenario D – Full Government Incentives, \$100/tonne CO_2 Tax

Strategy	Optimal number of fuel cell systems installed	Optimal installed fuel cell system capacity (MWe)	Optimal installed fuel cell system capacity as a percent of peak power (%)	Optimal installed fuel cell system capacity as a percent of average power (%)	Total costs of electricity and heat provision (\$/yr)	Total financial savings compared with base case of no fuel cells (\$/yr)	Annual cost savings (%)	Total carbon emissions (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (%)
I	34	6.8	25%	36%	\$27,202,559	\$9,031,919	25%	92,786	-43,566	-32%
II	48	9.6	36%	50%	\$29,079,093	\$7,155,385	20%	115,905	-20,447	-15%
III	57	11.4	42%	60%	\$31,483,385	\$4,751,093	13%	95,416	-40,936	-30%
IV	27	5.4	20%	28%	\$31,488,795	\$2,109,700	6%	93,124	-43,228	-32%
V	49	9.8	36%	51%	\$29,938,529	\$3,659,967	11%	89,707	-46,645	-34%

Table 11. Simulation results with government incentives and \$100/tonne CO_2 carbon tax

Simulation results are shown in **Table 11** for the scenario in which full state and federal incentives are applied, as well as a carbon tax at \$100/tonne CO_2. The most economical strategy remains Strategy I for Campustown, California and Strategy III for fuel cell manufacturers. As the carbon tax increases from \$0 to \$100/tonne CO_2, the top-most preferred strategy for each player (building owner or manufacturer) remains the same, and the optimal quantity of installations and resulting savings increase. By contrast, the most environmentally benign strategy changes from Strategy I to Strategy V (highlighted in blue). Strategy V achieves the highest reduction in CO_2 emissions, 34% of the base case.

Under Scenario D, one observes for the first time that the optimal solutions for three competing goals diverge completely. Under Scenario D, Strategy I achieves the most financial savings for building owners; Strategy III achieves the highest sales revenue for fuel cell manufacturers; Strategy V achieves the highest reduction in CO_2 emissions. One of the benefits of the *MERESS* model is that is enhances the ability of policy makers, GHG emission regulations, fuel cell manufacturers, and building owners to choose how they would like to address these competing goals.

3.6. Summary Trends Based on Scenarios B, C, and D

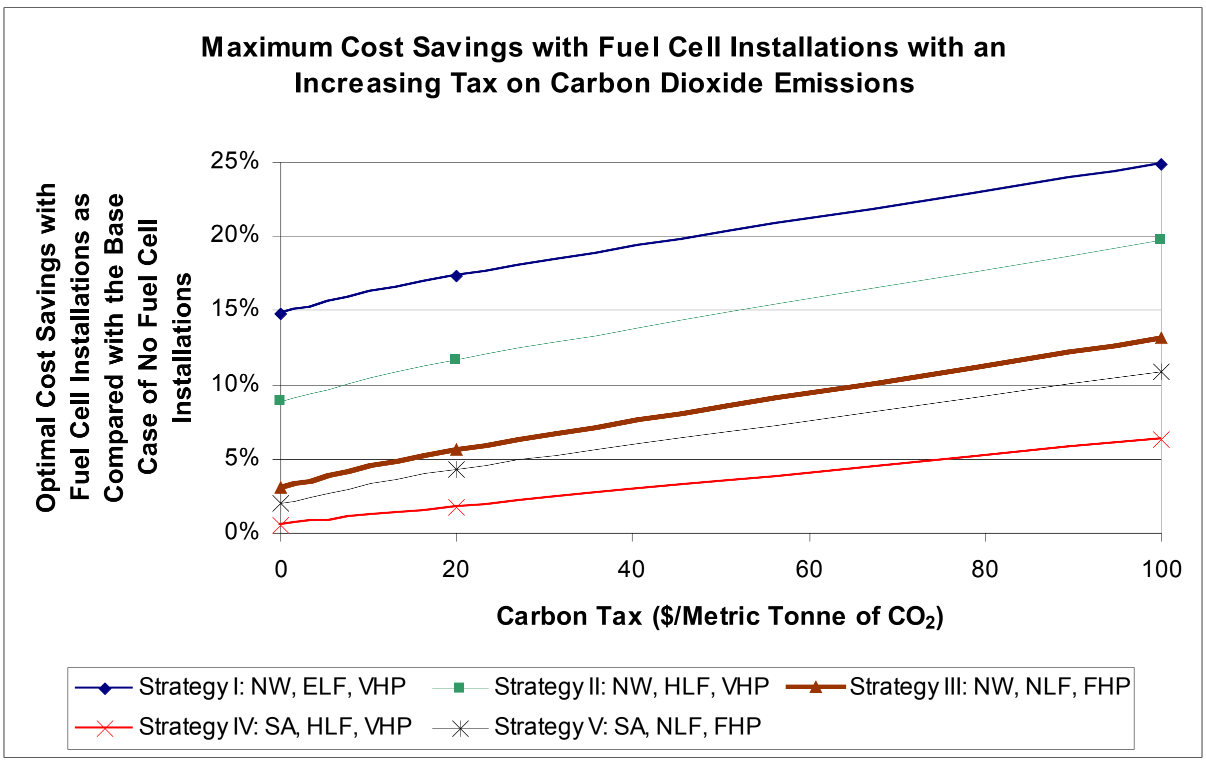

Figure 16. Best strategies for cost savings for building owners

Figure 16 shows the maximum cost savings to building owners in Campustown, California with the optimal quantity of FCSs installed across a range of carbon tax levels, for each of the five scenarios. The maximum savings is shown as a percentage of the base case costs with no fuel cells. The figure plots the data points for \$0, \$20, and \$100/tonne of CO_2 presented in previous tables and connects them with a curve fit. Regardless of carbon tax level, building owners save the most money by installing systems with Strategy I.

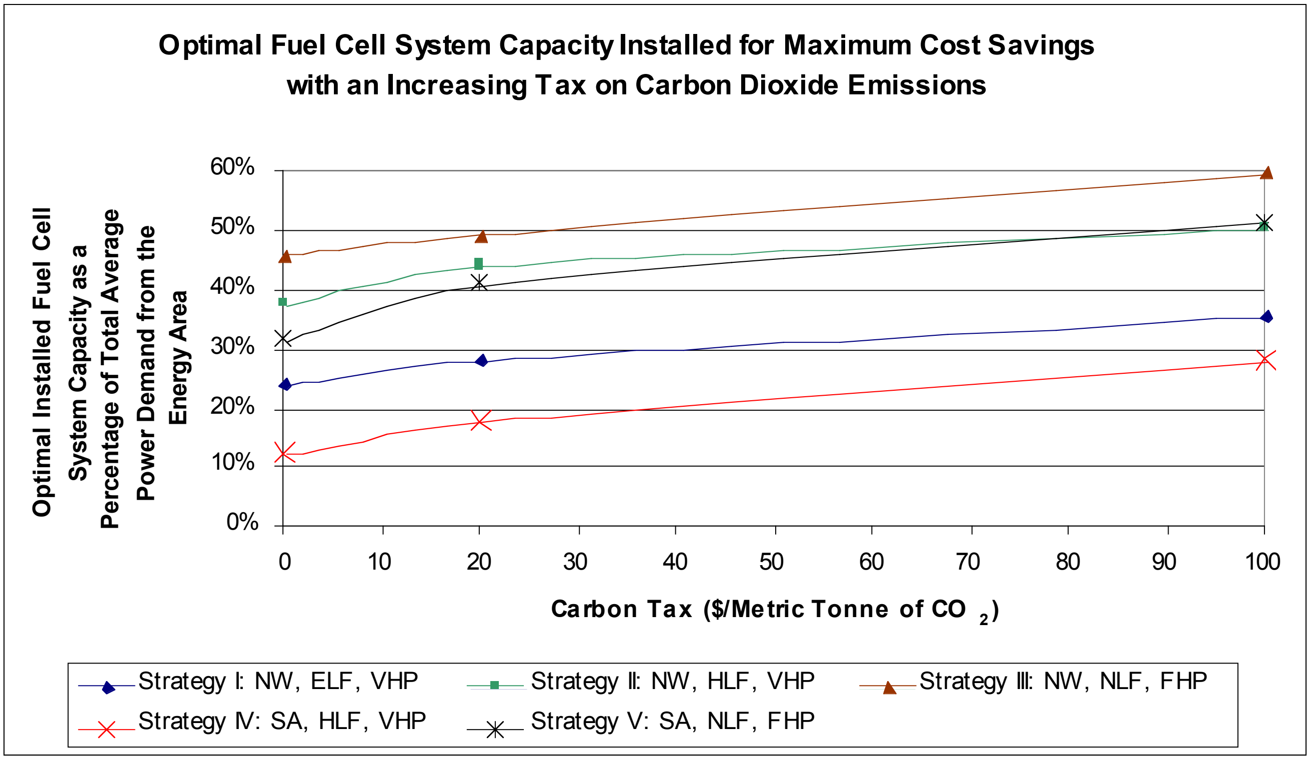

Figure 17. Best strategies for sales revenue for fuel cell manufacturers

Figure 17 shows the optimal installed electrical capacity of FCSs as a percentage of total average electrical demand in Campustown, California across a range of carbon tax levels, for each of the five scenarios. Again, the figure plots the data points for $0, $20, and $100/tonne of CO_2 presented in previous tables and connects them with a curve fit. Manufacturers typically associate profit maximization with maximal sales, or, in this case, installed capacity. A manufacturer achieves the highest sales with Strategy III, regardless of carbon tax level**.** Strategy II results in the second highest sales, initially. At higher carbon tax levels (around $85/tonne of CO_2, Strategy V results in the second highest sales.

A comparison of **Figures 7** and **8** underscores an important difference between the most economical installation and control strategies for building owners and that for fuel cell manufacturers. Resolving these diverse incentives could facilitate more effective system deployments and lower aggregate GHG emissions.

Figure 17 leads to an important conclusion for policy makers about the nature and extent of the subsidies they may consider: policy makers may be able to increase FCS penetration more effectively by incentivising certain types of strategies over others, rather than by instituting a large carbon tax. For example, for the analysis described here, moving from zero carbon tax to a $100/tonne carbon tax can increase the number of FCS installations under Strategy IV (bottom line) from 13% to 28% average capacity. By contrast, persuading manufacturers and building owners to switch from Strategy IV (bottom line) to Strategy III (top line), policy makers can increase the number of FCS installations from 13% to 46%, with no additional subsidy. Dollar-for-dollar, policy makers may find they can have the largest impact on FCS penetration by changing the way FCS are installed rather than by introducing a carbon tax.

Much of what initial subsidies try to do is to increase the number of new units manufactured. With greater levels of mass-production, the cost per unit falls, thereby achieving economies of scale. So as to bring costs down over time through economies of scale in mass-production, policy makers may consider initial incentives for manufacturers and building owners to install their systems according to Strategy III.

Beyond this, to accurately discuss future costs and potential cost reductions with mass-production, a separate research project would need to be conducted to perform a Design For Manufacturing Analysis (DMFA) on the design of a particular fuel cell system. Such a DFMA study would involve choosing a particular fuel cell type, fuel cell design, and system design, and deciding on reasonable advances in materials developments for that choice. Future costs can then be estimated based on the number of mass-produced components. Such studies take several months to perform properly and are beyond this project's original scope. They should call on previous fuel cell DFMA studies by Kuhn (1997) and James (1997).

3.7. Scenario E-1: Strategies for Maximizing Reductions in CO_2

Strategy	Optimal number of fuel cell systems installed	Optimal installed fuel cell system capacity (MWe)	Optimal installed fuel cell system capacity as a percent of peak power (%)	Optimal installed fuel cell system capacity as a percent of average power (%)	Total carbon emissions (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (Metric Tonnes of CO_2/yr)	Change in CO_2 compared with base case of no fuel cells (%)
I	38	7.6	28%	40%	92,335	-44,017	-32%
II	89	17.8	66%	94%	114,087	-22,265	-16%
III	81	16.2	60%	85%	93,268	-43,084	-32%
IV	54	10.8	40%	57%	104,526	-31,826	-23%
V	65	13.0	48%	68%	85,946	-50,406	-37%

Table 12. Best strategies for maximum CO_2 reductions

Table 12 shows simulation results for the hypothetical scenario in which a carbon tax at $1,000,000/tonne CO_2 is applied. The carbon tax is intentionally set to be unrealistically high so as to alter the function of the model. With an extremely high carbon tax, the model optimizes not for the highest financial savings, but rather for the highest reduction in CO_2 emissions. Setting the carbon tax at $1,000,000/tonne CO_2 reveals the strategies with the lowest CO_2 emissions and the highest CO_2 emission reductions. The strategies that achieve the highest CO_2 emission savings are Strategies I, III, and V with reductions of 32%, 32%, and 37%, respectively.

Strategy I is not only one of the strategies with the lowest CO_2 emissions; based on previous model runs, it is also the strategy with the highest financial savings for building owners. However, a dichotomy does exist between Strategy I and the strategy leading to the most sales revenue for fuel cell manufacturers. Of the scenarios shown, Strategy I results in the lowest capacity installment of FCSs, only 40% of average power demand. Therefore, Strategy I results in low sales revenue for fuel cell manufacturers.

By contrast, Strategy III is not only one of the strategies with the lowest CO_2 emissions; based on the results in **Table 12**, it is also one of the strategies with the highest installed capacity, 85% of average power demand. Therefore, Strategy III appears to be one of the most economical for fuel cell manufacturers while also achieving some of the largest CO_2 reductions.

Given these diverse incentives, fuel cell manufactures would probably prefer to move the installation and control strategy toward Strategy III, while building owners would prefer to move it towards Strategy I. Both achieve essentially the same reductions in CO_2 emissions.

Of all scenarios, Strategy V achieves the highest reductions in CO_2 emissions. However, as shown in **Figure 16**, Strategy V is the second least economical for building owners. As shown in **Figure 17,** Strategy V is the third least economical for fuel cell manufacturers, except in a certain high carbon tax range. At a carbon tax of about $85 per tonne of CO_2 and higher, Strategy V becomes the second most economical strategy for fuel cell manufacturers. However, at an even higher carbon tax, Strategy V is again the third least economical for manufacturers.

3.8. Scenario E-2 – Building Types for Maximizing CO_2 Reductions

If FCSs are installed SA (not NW), **Tables 11** and **12** show the best buildings for their installation for reducing CO_2 emissions, by building type and by the building name with the most similar load curve to that modeled. If Strategy IV is implemented, **Table 13** shows that, of the 30 buildings investigated, FCSs could be installed in 26 of them and achieve reductions in CO_2 emissions. Of these, the building load curve with the greatest potential for CO_2 emission reductions is that load curve most similar to the Mudd Chemistry building, a wet laboratory. Buildings with such load curves can be expected to achieve a potential 32% reduction in CO_2 emissions (highlighted in yellow). This building load curve is also the most economical installation for fuel cell manufacturers (based on the 13 installations shown in **Table 13**) and for building owners (based on a previous run shown in **Table 9**). Wet laboratories appear to be one of the more effective building types for CO_2 and cost reductions. However, no particular building type stands out as being better than the rest in all cases for CO_2 emission reductions. This result underscores the importance of testing the FCS's performance against the particular load curves of the buildings they may serve, rather than generalizing by building type alone

If Strategy V is implemented, **Table 14** shows that, of the 30 buildings investigated, FCSs could be installed in 26 of them and achieve reductions in CO_2 emissions. Of these, the building load curve with the greatest potential for CO_2 emission reductions is again that of the Mudd Chemistry building, a wet laboratory, with a potential 32% reduction in CO_2 emissions (highlighted in yellow). This building load curve is not the most economical installation for building owners (based on a previous run shown in **Table 9**), but it is one of the more economical installations. However, based on **Table 14**, the most economical installation for fuel cell manufacturers appears to be buildings with load curves most similar to the Center for Integrated Systems, another wet laboratory, highlighted in green with 12 installations.

Strategy IV: Best Buildings for Highest CO_2 Emission Reductions

Building Type	Load Curve Based on this Building	Optimal Number of Fuel Cell System Installations	Optimal Installed Fuel Cell System Capacity (MWe)	Optimal Installed Fuel Cell System Capacity as a Percentage of Peak Power Demand throughout Energy Area	Optimal Installed Fuel Cell System Capacity as a Percentage of Average Power Demand throughout Energy Area	Approximate CO_2 Emissions from Electricity and Heat Provision (metric tonnes CO2/yr)	Approximate Reduction in CO_2 Emissions Compared with Base Case of No Fuel Cells (metric tonnes CO2/yr)	Approximate Annual CO_2 Emission Savings Compared with the Base Case of No Fuel Cells (%)
Wet Lab	Mudd (Seeley G) Chemistry	13	2.6	10%	14%	11,974	5,730	32%
Offices/Classrooms	Braun Music	1	0.2	1%	1%	1,453	563	28%
Dry Lab	Ginzton (Edward L.) Labs & Annex	1	0.2	1%	1%	1,688	634	27%
Offices/Classrooms	Ceras	1	0.2	1%	1%	1,847	635	26%
Museum/Library	Cantor Center for Visual Arts	1	0.2	1%	1%	1,791	560	24%
Housing	Lagunita Dining	1	0.2	1%	1%	2,687	829	24%
Wet Lab	Gordon Moore Materials Research	4	0.8	3%	4%	7,536	2,291	23%
Dry Lab	Gates Computer Science	3	0.6	2%	3%	6,348	1,928	23%
Offices/Classrooms	Law Crown	3	0.6	2%	3%	4,765	1,401	23%
Offices/Classrooms	Tresidder	1	0.2	1%	1%	2,987	856	22%
Housing	Wilbur Dining Hall	1	0.2	1%	1%	2,303	638	22%
Other Type	Sweet	1	0.2	1%	1%	1,481	399	21%
Other Type	Faculty Club	1	0.2	1%	1%	1,481	399	21%
Wet Lab	Center for Integrated Systems (CIS)	6	1.2	4%	6%	19,710	5,297	21%
Housing	Stern Dining	2	0.4	1%	2%	2,331	605	21%
Offices/Classrooms	Packard Electrical Engineering	1	0.2	1%	1%	2,272	577	20%
Housing	Branner Hall	1	0.2	1%	1%	1,850	468	20%
Library	Green E	1	0.2	1%	1%	1,476	363	20%
Library	Meyer	1	0.2	1%	1%	1,476	363	20%
Offices/Classrooms	Lane History	1	0.2	1%	1%	809	82	9%
Dry Lab	McCullough (Jack A.)	1	0.2	1%	1%	1	0	6%
Housing	Florence Moore Kitchen	1	0.2	1%	1%	937	47	5%
Housing	Moore South	1	0.2	1%	1%	683	29	4%
Dry Lab	Mechanical Engineering Research Lab	1	0.2	1%	1%	1	0	4%
Dry Lab	Green Earth Sciences	1	0.2	1%	1%	1	0	3%
Housing	Xanadu	1	0.2	1%	1%	686	5	1%
Housing	Moore North	0	0	0%	0%	691	0	0%
Offices/Classrooms	Cummings Art	0	0	0%	0%	994	0	0%
Offices/Classrooms	TC Seq	0	0	0%	0%	850	0	0%
Dry Lab	Env Fluid Mech	0	0	0%	0%	0	0	0%

Table 13. Best building type load curves for maximum CO_2 reductions under Strategy IV

Strategy V: Best Buildings for Highest CO_2 Emission Reductions

Building Type	Load Curve Based on this Building	Optimal Number of Fuel Cell System Installations	Optimal Installed Fuel Cell System Capacity (MWe)	Optimal Installed Fuel Cell System Capacity as a Percentage of Peak Power Demand throughout Energy Area	Optimal Installed Fuel Cell System Capacity as a Percentage of Average Power Demand throughout Energy Area	Approximate CO_2 Emissions from Electricity and Heat Provision (metric tonnes CO_2/yr)	Approximate Reduction in CO2 Emissions Compared with Base Case of No Fuel Cells (metric tonnes CO2/yr)	Approximate Annual CO_2 Emission Savings (%)
Wet Lab	Mudd (Seeley G) Chemistry	9	1.8	7%	9%	12,240	5,730	32%
Offices/Classrooms	Braun Music	1	0.2	1%	1%	1,317	563	28%
Dry Lab	Ginzton (Edward L.) Labs & Annex	1	0.2	1%	1%	1,547	634	27%
Offices/Classrooms	Ceras	1	0.2	1%	1%	1,843	635	26%
Museum/Library	Cantor Center for Visual Arts	1	0.2	1%	1%	1,552	560	24%
Housing	Lagunita Dining	2	0.4	1%	2%	2,248	829	24%
Wet Lab	Gordon Moore Materials Research	6	1.2	4%	6%	6,815	2,291	23%
Dry Lab	Gates Computer Science	5	1	4%	5%	5,233	1,928	23%
Offices/Classrooms	Law Crown	3	0.6	2%	3%	4,793	1,401	23%
Offices/Classrooms	Tresidder	2	0.4	1%	2%	2,555	856	22%
Housing	Wilbur Dining Hall	2	0.4	1%	2%	2,021	638	22%
Other Type	Sweet	1	0.2	1%	1%	1,219	399	21%
Other Type	Faculty Club	1	0.2	1%	1%	1,219	399	21%
Wet Lab	Center for Integrated Systems (CIS)	12	2.4	9%	13%	16,918	5,297	21%
Housing	Stern Dining	2	0.4	1%	2%	2,247	605	21%
Offices/Classrooms	Packard Electrical Engineering	2	0.4	1%	2%	2,034	577	20%
Housing	Branner Hall	1	0.2	1%	1%	1,682	468	20%
Library	Green E	1	0.2	1%	1%	1,345	363	20%
Library	Meyer	1	0.2	1%	1%	1,345	363	20%
Offices/Classrooms	Lane History	0	0	0%	0%	891	82	9%
Dry Lab	McCullough (Jack A.)	3	0.6	2%	3%	3,394	0	6%
Housing	Florence Moore Kitchen	1	0.2	1%	1%	897	47	5%
Housing	Moore South	0	0	0%	0%	712	29	4%
Dry Lab	Mechanical Engineering Research Lab	3	0.6	2%	3%	4,154	0	4%
Dry Lab	Green Earth Sciences	3	0.6	2%	3%	3,735	0	3%
Housing	Xanadu	0	0	0%	0%	691	5	1%
Housing	Moore North	0	0	0%	0%	691	0	0%
Offices/Classrooms	Cummings Art	1	0.2	1%	1%	971	0	0%
Offices/Classrooms	TC Seq	0	0	0%	0%	850	0	0%
Dry Lab	Env Fluid Mech	0	0	0%	0%	597	0	0%

Table 14. Best building type load curves for maximum CO_2 reductions under Strategy V

3.9. Identification of Policy Options

Based on the results for Campustown, California, the research team identified several important policy options for California policy makers to encourage distributed energy network designs composed of FCSs that reduce GHG emissions.

- Create incentives for FCS manufacturers to build systems with a VHP
    - Strategies that implement FCSs with a VHP result in the highest financial savings in the costs of electricity and heat provision for building owners (Strategy I, in particular). The American FCS industry is composed of two major manufacturers that offer pre-commercial systems, Fuel Cell Energy and United Technologies Inc., neither of which offer systems with a VHP. As shown in this study, higher sales revenue for a FCS manufacturer is more highly correlated with a FHP, which they currently only offer. Although for them a VHP is an avant-garde design, the German fuel cell maker MTU does offer FCSs with a VHP as a feature. California policy makers could create incentives for American FCS manufacturers to offer this VHP feature as well.
- Create partnerships between FCS makers and energy service companies (ESCO) to consolidate incentives towards higher energy cost savings
    - The results showed a crucial difference between the strategy resulting in the highest sales revenue for fuel cell manufacturers (Strategy III) and the one with the highest energy cost savings for building owners (Strategy I). Furthermore, Strategy III is consistent with FCS manufacturers operating business-as-usual, designing their systems primarily as NLF with a FHP.
    - The results showed that a change away from the business-as-usual approach towards Strategy I would achieve not only higher energy and cost savings for building owners, but also higher CO_2 emission reductions.
    - To reconcile this dichotomy, policy makers can encourage FCS manufacturers to engage in financial partnerships with energy service companies (ESCO). Linking the financial incentives of FCS makers with ESCO has several benefits.
        - First of all, in such partnerships, the financial incentives of the FCS makers are linked with the downstream energy, cost, and emission savings of these systems. By partly owning and operating systems throughout their lifetime, FCS makers would be increasingly incentivized to build FCSs for maximum energy cost savings, since this objective would be aligned with their own profitability. For example, by forging such partnerships, it becomes in the manufacturer's interest to offer comprehensive and inexpensive O&M, to reduce initial FCS capital outlay costs, and to improve FCS reliability.
        - Second of all, FCS manufacturers bring a level of technical understanding of their systems that can reduce the perceived technical risk of investing in an installation and, consequently, reduce the project's cost of capital.

With this lower interest rate, these FCS installation projects are more economical. By contrast, financial institutions are more likely to over or under-estimate the technical risk associated with new technology projects without a detailed understanding of the underlying devices. This tendency is a type of economic inefficiency that some have addressed in the recent years by hiring more technical experts.

    - Third, an ESCO may be able to further reduce the cost of capital by partnering with educational institutions, which can borrow money at the very low bond rate in California. An ESCO may be able to more easily establish such links with universities and educational institutions than an individual FCS manufacturer.

    - Fourth, a major impediment to FCS installation projects has been the large initial capital cost to purchase systems. These large fixed costs ($1,000,000 or more per 200 kW system) exceed the typical annual budget ranges of facilities departments that operate buildings, a fact that reduces investment opportunities (Kulakowski 2007). By contrast, partnerships between ESCOs and FCS makers can eliminate these large initial capital outlays by creating annual contracts base on amortized costs or based on per unit electricity and heating pricing.

  - By co-owning FCSs over the duration of their investment time-horizon, FCS makers and ESCOs would be incentivized to both build and operate FCSs for maximum energy cost savings, since this objective would be aligned with their collective profitability.

- <u>Facilitate installing systems within pre-existing thermal networks as retrofits</u>

  - The Energy Commission could assist ESCO in locating pre-existing thermal networks within California. Many of these exist on the University of California campuses, and on corporate campuses. Some excellent retrofit opportunities may exist within the University of California (UC), including UC Berkeley, which heats buildings with a steam heating network.

  - The Energy Commission could also create financial incentives for connecting FCS to these identified pre-existing thermal networks, in particular if they are associated with state-owned educational institutions. This retrofit incentive program could be modeled after the Energy Commission's successful Solar Schools Program (SSP) (http://www.consumerenergycenter.org/school/solar-school.html.)

  - As mentioned previously, installations within the state's educational institutions may also have access to a lower cost of capital, because these institutions can often borrow at the bond rate for educational projects (Canellos 2003).

- <u>Implement *MERESS* to identify specific state-owned buildings ideal for installation</u>

  - The results of this analysis showed that no one building type (such as a wet laboratory) was always superior to another building type (such as a residence) for CO_2 emission reductions or for energy cost savings. The shape of the buildings electricity and heating demand curves (load curves) over time influence how effectively available heat from FCS will be consumed, and what portion of this available heat will be wasted to the environment as unrecovered heat. *MERESS* showed that it could successfully identify the load curves of particular buildings (such as the Mudd Chemistry Building) that had the highest environmental and financial savings.

- As a result, the research team strongly encourages the Energy Commission to apply the *MERESS* model to load curves for state-owned buildings, to determine the buildings with the ideal load curves.

4.0 Conclusions and Recommendations

4.1. Building Types

In evaluating GHG emission reductions with the use of FCSs in California buildings, for the California buildings and town evaluated here, the research team concludes:

- The electricity and heating load curves of individual buildings are extremely important in determining the economics and GHG emission reduction from an installation.
- These load curves are extremely important because the strategy that achieves the highest reductions in CO_2 emissions is with stand alone (SA) operation, in which one or a few FCSs manipulate their operation to meet the instantaneous electricity and heating demand from these buildings described by their load curves, without additional back-up or buffer of a surrounding electrical or thermal network.
- Specifically, at the highest incentive levels, the highest reductions in CO_2 emissions were observed with Strategy V, which incorporates stand alone (SA) operation, heat load following (HLF), and a fixed heat-to-power ratio (FHP).
- If one were to imagine this scenario, it would be analogous to cutting the electricity lines to one's house and powering it with the electricity from a stand-alone generator and its waste heat alone.
- For this stand alone strategy (Strategy V), Table 14 summarizes the best building type load curves for maximum CO_2 reductions. The top three of these load curves (Mudd, Braun, and Ginzton) are plotted in Figures 9 and 10.
- For this stand alone strategy (Strategy V), Table 9 shows the building load curves that achieve the most cost savings for building owners in procuring electricity and heat.
- For this stand alone strategy (Strategy V), the building load curve with the greatest reductions in CO_2 emissions is Mudd, a wet laboratory. Mudd is not the most economical building for installation, but it is one of the more economical buildings for installation, for both FCS manufacturers (as shown by the total number of installations) and building owners (as shown by their economic savings in Table 9.)
- Wet laboratories like Mudd are similar in their energy requirements to many industrial facilities, which also operate around-the-clock at high energy consumption levels. Wet laboratories appear to be one of the more effective building types for CO_2 and cost reductions. However, no particular building type stands out as being better than the rest in all cases for CO_2 emission reductions. This result underscores the importance of testing the FCS's performance against the particular load curves of the buildings they may serve, rather than generalizing by building type alone
- No particular building type (such as a wet laboratory or residence) stands out as maximizing any of these three goals consistently, across strategies: GHG emission reductions, cost savings to building owners, and high FCS manufacturer sales revenue.

- This last point above underscores the pivotal role that the *MERESS* model can play in being able to test out a particular building's load curves. Because it is difficult to generalize results by building type across strategies, the *MERESS* model can play an essential role in informing users about the GHG emission reductions and economics of installing a system in one building over another. Rather than relying on generalized rules of thumb organized by building types, users can garners more accurate results by actively testing a FCS's performance against particular load curves of a building it might serve.

If readers do not have the opportunity to run the *MERESS* model against their own data to evaluate specific buildings relevant to them, they can make broad analogies between college campus buildings and their own buildings to draw general guidance. Although a PIER project is currently measuring the diurnal/seasonal energy use patterns for a number of businesses, most business either do not record their building demand data in fine enough time increments or do not make these data publicly available. Businesses often cite time constraints or retaining their competitive advantage over other businesses. Without such available data, this study can be used to approximate commercial and manufacturing building behavior with campus buildings. College buildings modeled in this study that most closely approximate commercial buildings include offices, classrooms, museums, and libraries. College buildings modeled here that most closely approximate manufacturing buildings include wet and dry laboratories. Until more businesses begin measuring their energy use data in detail and make these data available, these analogies can be used to draw broad guidance for commercial and industrial facilities.

4.2. Network Configurations

In evaluating GHG emission reductions with the use of FCSs under different network configurations, for the California buildings and town evaluated here, the research team concludes:

- Under Scenario D, with full government incentives and a $100/tonne CO_2 tax, three different strategies achieve the highest GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue:
    - Strategy V achieves the highest reductions in CO_2 emissions.
    - Strategy I provides energy for building owners with the lowest total cost, including the fixed and variable costs of resources and fuel over the investment time horizon.
    - Strategy III provides the highest sales revenue for fuel cell manufacturers
- Strategy V achieves the highest reductions in CO_2 emissions. Strategy V incorporates stand alone (SA) operation, heat load following (HLF), and a fixed heat-to-power ratio (FHP) [SA, HLF, FHP]. It results in a maximum CO_2 emission reduction of 37% relative to a base case of no FCSs installed.
- Strategy I is most economical for building owners. Strategy I incorporates electrically and thermally networked (NW), electricity power load following (ELF), and VHP [NW,

ELF, VHP]. The town's building owners gain the highest cost savings, 25% relative to a base case with no fuel cells and under full incentives and a $100/tonne CO_2 tax. Figure 16 summarizes the best strategies for cost savings for building owners.

- Without any state and federal incentives or carbon tax, Strategy I is economical, although marginally so, with 3% cost savings, and a 29% reduction in CO_2 emissions. The significance of this finding is to demonstrate that just by changing the installation and operating strategy for FCSs, they can be installed economically, without any governmental incentives. FCSs have not typically been designed and installed to be connected to thermal networks, to follow electrical loads, and to achieve a VHP, either separately or in concert.
- Strategy III is most economical for fuel cell manufacturers. Strategy III is NW, NLF, with a fixed heat-to-power ratio (FHP) [NW, NLF, FHP]. Figure 17 summarizes the best strategies for high FCS manufacturer sales revenue.
- Strategy III results in 44 FCSs or 46% of average electrical power installed. However, this strategy results in an annual energy cost savings of only 3%. These simulations illustrate a striking dichotomy between the most economical strategy for building owners and the most economical strategy for fuel cell manufacturers. This dichotomy pervades most scenarios.
- Strategies III and V are consistent with the way that FCS manufacturers design their systems today, primarily as NLF with a FHP.
- By contrast, Strategy I is avant-garde for the fuel cell industry, in particular, in its use of a VHP.
- In all scenarios evaluated, higher energy cost savings are achieved with linking FCSs together in electrical and thermal networks, as opposed to installing them SA.
- When NW, combining either electrical or thermal load following with VHP improved economic performance.

To draw these generalized conclusions, the research team bracketed uncertainties via federal and state incentives, two levels of carbon tax, and five different operating strategies. The largest variations occur with the changes in operating strategies, which users of the *MERESS* model can exercise complete control over. Although this analysis is representative of widely-accepted FCS operating data and of building demand applications, input data are historic and could change in the future. The research team leaves users to tailor *MERESS* to their specific niche market applications.

4.3. Policy Recommendations

In the course of developing these conclusions, the research team identified four key policy options available to California for encouraging the design of distributed energy networks that reduce GHG emissions:

- Create incentives for FCS manufacturers to build systems with a VHP,
- Create partnerships between FCS makers and energy service companies (ESCO),

- Facilitate installing systems within pre-existing thermal networks, and
- Implement *MERESS* to identify specific state-owned buildings ideal for installation.

If implemented, these recommendations would give the state the greatest long-term environmental improvement for each dollar spent. It may be possible to implement these recommendations at fairly low cost, since they do not involve increasing financial incentives or directly financing hardware. Rather, they involve the more time-consuming and complex processes of better communications and cooperation among parties with diverse interests, and the delicate dance of persuading people to think differently, and change their minds and actions. With such an approach, for example, the state could ensure better implementation of Strategy I [NW, ELF, VHP], still avant-garde for the American FCS industry, and, consequently reduce the dependency of this industry on government-financed incentives.

Furthermore, for the state and others to appreciate FCSs for their reductions in GHG emissions, the state needs to implement more precise GHG accounting procedures and inventory of historical emissions. One suggestion for improving the inventory is to critically evaluate the state's inventory. Another suggestion is to count FCSs consuming biogas not as zero GHG contributors but as *net negative* contributors, because they convert each molecule of CH_4 that would be otherwise emitted into the atmosphere into a molecule of CO_2, which has 23 times less the global warming impact as CH_4 over a 100-year period.

Additional approaches should also be considered in parallel. For example, dollar-for-dollar, policy makers may find they can have the largest impact on FCS penetration by changing the way FCS are installed rather than by introducing a carbon tax. Much of what initial subsidies try to do is to increase the number of new units manufactured. With greater levels of mass-production, the cost per unit falls, thereby achieving economies of scale. So as to bring costs down over time through economies of scale in mass-production, policy makers may consider initial incentives for manufacturers and building owners to install their systems according to Strategy III [NW, NLF, FHP]. In this way, policy makers may be able to increase FCS penetration more effectively by incentivising certain types of strategies over others, rather than by instituting a large carbon tax.

4.4. Recommendations for Future Research

- The DOE's Hydrogen and Fuel Cell Program (http://www.hydrogen.energy.gov/) has historically focused almost entirely on implementing PEM fuel cells in cars. It has spent significantly less funding on developing stationary FCSs for electricity and heat provision for buildings. The Energy Commission could play a crucial role in closing this technology development gap by funding additional research and development of stationary FCSs.
- This study's results suggest the need to expand the fuel cell research paradigm from beyond device-level electrical efficiency and power density to optimizing FCSs within the context of their ultimate end-use environment. The research team recommends further expansion of the *MERESS* model to include more permutations of FCS design and economics, and more building use data.

- Specifically, it would be helpful to expand the MERESS model to address the additional constraint of the second law of thermodynamics, which indicates that heat can only flow from hot to cold regions and not vice versa without external work applied. To address second law constraints, it would be helpful to have additional data on the temperatures at which heat is needed in buildings. Although load curves exist for the total quantity of heat demanded over time (kWh) for some individual buildings, very little data have been methodically compiled associating the quantity of heat demanded with the temperatures at which it is needed. Federal and state agencies would benefit from gathering data not only on the quantity of heat demanded over time, but also the temperatures at which it is demanded for industrial, commercial, and residential buildings.
- At the aggregate level, it would also be helpful to have more precise data on the quantity of heat demanded over time in the state of California, in different sectors, and perhaps even by building. Although individual buildings may collect these data in some form (sporadically), state and federal agencies do not collect and compile these data from the multitude of demand sources. To appropriately track thermal demand over time and efficiency improvements in this area from implementing CHP FCSs, it would be extremely helpful for federal and state agencies to obtain measurements on and compile these data.

4.5. Benefits to California

California has already received several benefits from this contract:

- Californians have gained access to a simulation tool, the *MERESS* model, which can be run off of most computers, that allows them to evaluate installing a fuel cell system (FCS) in a particular California building or town.
- Reading the report and running the *MERESS* simulation tool allows policy makers, FCS manufacturers, and building owners to gain a better understanding of how to design, install, and control FCSs to maximize reductions in GHG emissions and costs.
- The *MERESS* model helps users make more informed decisions about the trade-offs among three important, but often competing goals: GHG emission reductions, cost savings to building owners in procuring electricity and heat, and high FCS manufacturer sales revenue.
- The *MERESS* model shows fundamentally unique and important engineering approaches to designing, installing, and operating FCSs. Although these approaches have not typically been pursued by FCS developers or building owners, each can gain financial savings and environmental benefits by implementing them.
- Californians have gained a third-party, independent, expert evaluation of CO_2 emissions and costs from FCSs. In so doing, this research effort has reduced the asymmetry of information between technology developers and implementers, lessened a significant market failure in the commercialization of a productivity-enhancing technology, and aided its potential economic growth.
- Californians have gained a more accurate GHG emission inventory and well-informed advice on how to improve GHG accounting procedures and historical data series.

California will receive additional benefits from this contract in the future:

- If policy makers, FCS manufacturers, and building owners implement the recommendations presented by the *MERESS* model, they could more effectively direct their technology investments and save millions of dollars in avoided government subsidies and misguided development efforts.
- Building owners can use their own unique electricity and heating demand curves and the simulation capability developed here with the *MERESS* model to evaluate the environmental and financial impact of installing a FCS in their own buildings. They can make more environmentally and financially informed decisions in this manner.
- The state could evaluate its own state-owned buildings to determine which of these state-owned buildings would allow for the greatest reductions in CO_2 emissions and costs with FCS installations.
- Implementing the *MERESS* model to design networks of CHP FCSs could result in extensive GHG emission reductions, even if these systems are fueled by natural gas (not just hydrogen). Installation of the systems would provide greater fuel efficiency, which results in less fuel consumption and lower GHG emissions.
- In gaining access to a more accurate GHG emission inventory and well-informed advice on how to improve GHG accounting procedures and historical data series, Californians have also gained the opportunity to more accurately track improvements in GHG emission reductions and to more precisely set reduction goals.
- If applied, the *MERESS* model and these results can have a game-changing effect on the fuel cell industry.

4.6. Final Conclusions

Californians have gained access to a simulation tool, the Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*) model, which allows them to evaluate the environmental and financial impacts of installing fuel cell systems (FCSs) in a California buildings and towns. The *MERESS* model allows users to explore unique operating strategies that commercial industry has typically overlooked, and to evaluate trade-offs among three important, but often competing goals: greenhouse gas (GHG) emission reductions, cost savings to building owners in procuring electricity and heat, and high FCS manufacturer sales revenue. Initial runs of the *MERESS* model show that these competing goals are maximized with different installation and operating strategies, but that all three goals can be reasonably met with a single approach. Although no particular building type stands out as consistently achieving the highest carbon dioxide (CO_2) emission reductions and cost savings, certain load curves of building are clear winners. Rather than reply on generalized results according to building type, building owners, policy makers, and fuel cell manufacturers would benefit most by continually using the *MERESS* model to guide and update installation decisions.

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Glossary of Abbreviations and Acronyms

Abbreviation	Description
BTU	British Thermal Units
CA	California State
CARB	California Air Resources Board
CCGT	combined cycle natural gas turbine(s)
CHP	combined-heat-and-power (cogeneration)
CH_4	methane gas
CO_2	carbon dioxide gas
CPUC	California Public Utilities Commission
Cty	county
DC	direct current
DFMA	Design for Manufacturing Analysis
DOE	U.S. Department of Energy
EIA	Energy Information Administration (part of the U.S. DOE)
ELF	electricity load following
EPA	Environmental Protection Agency (U.S.)
ESCO	energy services companies
FCS	fuel cell system
FCSs	fuel cell systems
FHP	fixed heat-to-power ratio
GE	General Electric Corporation
GHG	greenhouse gas
GIS	geographic information system
GJ	gigajoule or gigajoules
HHV	higher heating value
HLF	heat load following
HOMER	Hybrid Optimization Model for Electric Renewables
HVAC	heating, ventilating, and air-conditioning
H_2	molectular hydrogen
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram or kilograms
kW	kilowatt or kilowatts
kWe	kilowatt or kilowatts of electric power

Abbreviation	Description
kWh	kilowatt hour or hours
kWhe	kilowatt hour or hours of electric power
LBNL	Lawrence Berkeley National Laboratories
LHV	lower heating value
LLNL	Lawrence Livermore National Laboratory
MCFC	Molten Carbonate Fuel Cell
MERESS	Maximizing Emission Reductions and Economic Savings Simulator
MMT	Million Metric Tonnes
Mo	Month
MT	Metric Tonnes
MW	megawatt or megawatts
MWe	megawatt or megawatts of electric power
MWh	megawatt hour or hours
NLF	no load following
O&M	operations and maintenance
PAFC	phosphoric acid fuel cell
PNGV	Partnership for a New Generation of Vehicle (U.S. DOE program)
Quad	1E12 BTU
NW	networked
NREL	National Renewable Energy Laboratory
PEM	proton-exchange membrane
PG&E	Pacific Gas and Electric Corporation
PIER	Public Interest Energy Research Program
SA	stand alone
SGIP	Self-Generation Incentive Program (California State)
SSP	Solar Schools Program
UC	University of California
U.S.	United States
UTC	United Technologies Corporation
VHP	variable heat-to-power ratio
_e_max	maximum electrical efficiency

Appendix A

The authors' analysis of the CEC database was additional to what the authors were contracted to provide. The authors' evolving findings were offered to the CEC in good faith. The relevance of the latter to this report is the comparison of fuel cell systems to conventional systems with respect to greenhouse gas emissions; this was what led the authors to look at the baseline inventories issues in the first place. The authors hope that these additional efforts can be received in the spirit in which the authors performed those re-analysis—to help the state toward a consistent baseline method that will mesh with newly passed laws for greenhouse emissions reductions for which best methods are essential, and to help do comparative emissions for conventional and fuel cell power plant systems. The authors only hope to advance that dialog, not do a thorough analysis of it within this particular research report.

Abstract on the topic of *Getting the Baseline Right: Reconciling Greenhouse Gas Accounting Data and Methodologies* by Whitney G. Colella, Stephen H. Schneider, and Daniel M. Kammen:

> *"The California Global Warming Solutions Act (AB32) is the most aggressive economy-wide effort to address greenhouse gas (GHG) emissions to date, mandating a return to 1990 emissions levels by 2020. We have found a 34% difference in reported in-state emissions from electricity generation as compiled by the lead state and federal agencies. In the 'business as usual' case, this amounts to differences in total in-state emissions by 2010 of 26%, 22% by 2020 and 15% by 2050. Adjusting the baseline upwards to reflect the true baseline, instead of a total required reduction of 73.7 million metric tonnes (MMT) of carbon dioxide (CO_2) using the lower baseline emissions estimate, a total reduction of 82.5 MMTCO_2 will instead be required by 2050 to comply with AB32. Combined heat and power (CHP) plants can raise the effective efficiency of power plants from ~ 40% to over 70%, and thereby lower their CO_2 emissions per unit of useful work. However, our analysis shows that consistent CO_2 reporting methods must be applied to CHP plants to avoid the sort of over-counting of benefits that we found in the state of California data. Moreover, inter-annual variations in the weather and in economic activity make the use of any single year as a baseline more susceptible to sampling problems, which can be corrected if the single-year baseline is instead replaced with a multi-year running average. In the expanding set of cities, states and nations pursuing GHG reduction legislation, developing standardized GHG monitoring and accounting methodologies is critically important environmentally and economically."*

Appendix B

STATE OF CALIFORNIA – THE RESOURCES AGENCY　　GRAY DAVIS, Governor

CALIFORNIA ENERGY COMMISSION
1516 NINTH STREET
SACRAMENTO, CA 95814-5512

February 26, 2007

Dr. Whitney Colella
Stanford University
P.O. Box 19546
Stanford, CA 94309-9546

Subject: Review of Greenhouse Gas Emissions from In-State Electricity Production

Dear Dr. Colella:

Thank you for helping to improve the California Greenhouse Gas (GHG) emissions inventory, specifically GHG emissions from in-state fossil fuel combustion for electricity production.

Thank you for spending a considerable amount of time digging into the California Energy Commission's data and identifying the need for a revision. Thank you for reviewing in detail our assumptions, calculations, and multiple databases for estimating carbon dioxide (CO_2) emissions. You correctly identified that the Energy Commission was under-estimating the state's CO_2 emissions and correctly pointed to sources of these errors. Without your questions, emails, phone calls, and suggestions over the past five months, we would not have located any of these errors. We appreciate that you have spent a significant amount of time successfully suggesting corrections to our data.

Your efforts have resulted in correction of several errors in our *Inventory of California GHG Emissions and Sinks: 1990 to 2004*. For example, on February 2, 2007, we issued a memo entitled "Revisions to the 1990 to 2004 Greenhouse Gas Emissions Inventory Report" that delineates the precise cell-by-cell locations of corrections that you helped identify. This memo can be downloaded at http://www.climatechange.ca.gov/policies/greenhouse_gas_inventory/index.html.

Thank you for taking the time to constructively critique and correct our data. As a result of your efforts, we have increased the estimated CO_2 emissions from in-state fossil fuel combustion for electricity generation by approximately 10 percent and the overall sector net GHG emissions by 0.7 to 1.7 percent, depending on the year.

Sincerely,

ROSELLA SHAPIRO
Deputy Director
Fuels & Transportation Division
California Energy Commission

Sincerely,

GERALD R. BEMIS
Special Projects Office
California Energy Commission

Appendix C

We relied on federal data for electricity and emission data as much as possible due to a greater level of confidence with these data. Federal data from EIA are the original/primary source of California electricity data later published by the CEC. We applied the following methodology to derive CO_2 emissions in California from electricity consumption:

1) We used a federal data set, EIA Monthly Electricity Sales Data 1990-2004, for California.
2) We used a second federal data, EIA Annual Direct Use Data 1990-2004, and applied the monthly distribution from the Sales data.
3) We derived total electricity consumption as the sum of this sales data and this direct use data mentioned in (1) and (2) above: Sales + Direct Use = Total Electricity Consumption
4) We used a third federal data set, EIA Annual Net Generation Data 1990-2004, and again applied the monthly distribution from the Sales data.
5) We derived total imported electricity from the total consumption and net generation data: Imports = Total Consumption – Net Generation
6) We derived the CO_2 emission factor for net generation by dividing the EIA CO_2 emission data for net generation (from a fourth federal data set) by the total net electricity generation data (from 3 above): EIA Total CO_2 Emissions from Net Generation/EIA Net Generation = CO_2 Emissions Factor for Net Generation
7) We then applied this annual average emission factor to the monthly electricity generation data to derive the Total CO_2 Emissions from Net Generation on a monthly basis.
8) Similarly, because federal data are not compiled for CO_2 emissions from imported electricity into California, we derived the CO_2 emission factor for imported electricity from CEC data, according to this formula: CEC Total CO_2 Emissions from Imports/CEC Electricity Imports = CO_2 Emissions Factor for Imports
9) We then calculated the total CO_2 emissions from imported electricity as the produce of this CO_2 emission factor and the imported electricity data: EIA Imports * CO_2 Emissions Factor for Imports = Total CO2 Emissions from Imports (Monthly)
10) We redistributed these data across the state of California by population.

We visualized CO_2 emission changes according to the following methodology:

1) A custom Geographic Information System (GIS) application was applied.
2) CO_2 is plotted at point of consumption, not generation, to link cause and effect. The environment is scientifically understood to be indifferent to the location of CO_2 emissions (unlike air pollution).
3) The units of the plot in Figure 8 are Metric Tonnes (MT) per month (Mo) per county (Cty).

4) Blue & Green colors are “good,” indicating a reduction in CO_2 emissions; Red and Black are “bad,” indicating an increase in CO_2 emissions.

5) Figure 8 uses a Sigmodial Plot. The colors are applied sigmoidally to these data to highlight variations at the low end. The top legend plots these data values linearly. The bottom legend plots the color spectrum linearly.

Appendix D

The steam heating price of $0.056/kWh is derived as follows. The steam price has three major components: energy cost (65%), the combined distribution system and plant operations and maintenance (O&M) (20%), and debt from capital projects (15%). Mr. Dean Murray of the Stanford Utilities Department estimated that the portion of each of these associated with the steam power plant and not the steam pipe distribution network was 100%, 50%, and 25%, respectively (Murray 2006-2007). If one multiplies these numbers together (65%*1.00+20%*0.5+15%*0.25 = 78.75%), one can estimate that approximately 78.75% of the University's charged steam price is associated with the steam power plant and not the steam pipe distribution networks. The steam heating price is then calculated as the product of 78.75% and University's listed price for steam ($20.12 per 1,000lbs), which equates to $0.056/kWh.

The electricity price is derived in a similar manner. The electricity price has three major components: energy cost (70%), distribution system and O&M (17%), and debt (13%). Mr. Murray estimated that the portion of each of these associated with the electricity power plant and not the low-voltage electricity distribution network was 100%, 50%, and 25%, respectively (Murray 2006-2007). If one multiplies these numbers together (70%*1.00+17%*0.5+13%*0.25 = 81.75%), one can estimate that approximately 81.75% of the University's charged electricity price is associated with the electricity power plant and not the distribution wires. The electricity price is then calculated as the product of 81.75% and University's listed FY08 price for electricity ($0.1035 per kWh of electricity), which equates to $$0.085/kWh.