Title

Enabling the Distributed Generation Market of High Temperature Fuel Cell and Absorption Chiller Systems to Support Critical and Commercial Loads

Author

DiMola, Ashley M.

Publication Date

2015

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA,

IRVINE

Enabling the Distributed Generation Market of High Temperature Fuel Cell and Absorption Chiller Systems to Support Critical and Commercial Loads

THESIS

submitted in partial satisfaction of the requirements

for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

Ashley M. DiMola

Thesis Committee:

Professor G. Scott Samuelsen, Chair
Professor Jacob Brouwer
Professor Faryar Jabbari

2015

DEDICATION

To Paul, of course

Thank you for your love, support, and encouragement.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

NOMENCLATURE

ADV	Ad valorem tax
DG	Distributed Generation
DOE	Design of Experiments
GHGs	Greenhouse Gases
HRU	Heat recovery unit
HTFC/AC	High temperature fuel cell and absorption chiller
Im/Ex	Imports and exports
IPCC	Intergovernmental Panel on Climate Change
MWh	Megawatt Hour (of electricity)
LBVA	Long Beach Veteran's Affairs Hospital
LCOE	Levelized cost of electricity
MSTB	Multipurpose Science & Technology Building
NG	Natural gas
O&M	Operation & maintenance
SCAQMD	South Coast Air Quality Management District
TES	Thermal Energy Storage tank

ACKNOWLEDGMENTS

First and foremost, I would like to acknowledge Professor G. Scott Samuelsen for his visionary leadership at the Advanced Power and Energy Program. This thesis is a direct result of his knowledge and passion for clean-energy solutions.

I would also like to acknowledge Mr. Richard Hack for his input in the detailed engineering aspects of the HTFC/AC deployment, Professor Jacob Brouwer for help directing this thesis, and Mr. Brendan Shaffer for his guidance and support.

Along with Professor Samuelsen and the staff at APEP, the following people were instrumental in making this project a success.

- Mr. Kyle Hosford, Mrs. Sarah Martz, and Dr. Pere Margalef for building a strong foundation of research in HTFC/AC technology at APEP.
- Dr. Lori Schell for creating the economics model and for being a wonderful research partner and inspiring leader.
- Mr. Leon Roach and Mr. Nato Flores of the University of California, Irvine Medical Center (UCIMC) for their support in making APEP's idea for a full-scale HTFC/AC prototype a reality.
- Mr. Robert Flores for his patience and continual support in helping trouble-shoot the Matlab® codes.
- Mr. Chad Atalla for helping to create the data acquisition platform which will be deployed at UCIMC.

ABSTRACT OF THE THESIS

Enabling the Distributed Generation Market of High Temperature Fuel Cell and Absorption Chiller Systems to Support Critical and Commercial Loads

by

Ashley M. DiMola

Master of Science in Mechanical and Aerospace Engineering

University of California, Irvine, 2015

Professor G. Scott Samuelsen, Chair

Buildings account for over 18% of the world's anthropogenic Greenhouse Gas (GHG) emissions. As a result, a technology that can offset GHG emissions associated with buildings has the potential to save over 9 Giga-tons of GHG emissions per year. High temperature fuel cell and absorption chiller (HTFC/AC) technology offers a relatively low-carbon option for meeting cooling and electric loads for buildings while producing almost no criteria pollutants. GHG emissions in the state of California would decrease by 7.48 million metric tons per year if every commercial building in the State used HTFC/AC technology to meet its power and cooling requirements. In order to realize the benefits of HTFC/AC technology on a wide scale, the distributed generation market needs to be exposed to the technology and informed of its economic viability and real-world potential.

This work characterizes the economics associated with HTFC/AC technology using select scenarios that are representative of realistic applications. The financial impacts of various input factors are evaluated and the HTFC/AC simulations are compared to the economics of traditional building utilities. It is shown that, in addition to the emissions reductions derived from the systems, HTFC/AC technology is financially preferable in all of the scenarios evaluated. This work also presents the design of a showcase environment, centered on a beta-test application, that presents (1) system operating data gathered using a custom data acquisition module, and (2) HTFC/AC technology in a clear and approachable manner in order to serve the target audience of market stakeholders.

1 INTRODUCTION

1.1 GOAL

The goal of this Thesis is to enhance the distributed generation market potential of high temperature fuel cell and absorption chiller (HTFC/AC) systems through rigorous modeling of the economic attributes of HTFC/AC system in combination with a robust demonstration.

1.2 OBJECTIVES

The following objectives are addressed to meet the goal of this research:

I. Analyze the financial viability of megawatt-class high temperature fuel cell and absorption chiller systems.

II. Create a high temperature fuel cell and absorption chiller system technology transfer platform.

2 BACKGROUND

2.1 GLOBAL CLIMATE CHANGE

The Intergovernmental Panel on Climate Change (IPCC) reported in their 2013 Fifth Assessment Report that the average combined land and ocean surface temperature on earth has risen 0.85 degrees Celsius (1.53^{o}F) since preindustrial times [1]. According to the IPCC's Working Group I Summary for Policy Makers, "It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century." Anthropogenic forcing factors causing this rise in temperature primarily consist of industrial processes such as energy production which emit large amounts of carbon dioxide (CO_2). CO_2 acts as a greenhouse gas; it collects in the earth's troposphere and causes an imbalance in radiative forcing [1].

The earth's energy content is derived from radiant energy received from the sun. The amount of energy on earth remains constant when the amount of radiation received from the sun is equal to the amount of energy emitted by earth. However, if the balance is off, the energy content of the earth will change accordingly. Greenhouse gases such as CO_2 absorb radiation in the thermal spectrum of the sun, but do not emit radiation in the thermal spectrum of the earth, thus causing a net increase in the earth's energy content. Many greenhouse gases produce the same effect as CO_2 including methane, nitrous oxide, sulfur hexafluoride, and others [2]. The reason many studies focus solely on CO_2 is that it is the most prevalent greenhouse gas. In studies that do account for more than just CO_2, over-all greenhouse gas emissions are simplified using a term called *CO_2-equivalent*. The California Air Resources Board defines CO_2-equivalent as the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas [3]. Using this term, it is possible to aggregate all of the greenhouse gas emissions into one reportable number.

The IPCC Fifth Assessment Report projects the future increase in earth's mean surface temperature using four different Representative Concentration Pathways (RCPs). RCP 2.6, 4.5, 6.0 and 8.5 represent scenarios in which the radiative forcing in the year 2100 is 2.6 W/m^2, 4.5 W/m^2, 6.0 W/m^2 and 8.5W/m^2 respectively. These fluxes correlate with a concentration of CO_2-equivalent gases in the earth's atmosphere of 421, 538, 670, and 936 ppm respectively. The observed trend of earth's CO_2-equivalent atmospheric concentrations correlate most closely with the middle RCPs. RCP 2.6 is a very low concentration pathway that would be difficult to achieve without taking drastic measures. RCP 8.5 is a very high concentration pathway and represents what concentrations could become if the world continues on its path of industrialization without addressing greenhouse gas emissions [5]. Figure 1 displays the historical and projected change in global average surface temperature through the year 2100 based on measured data and the four RCP scenarios.

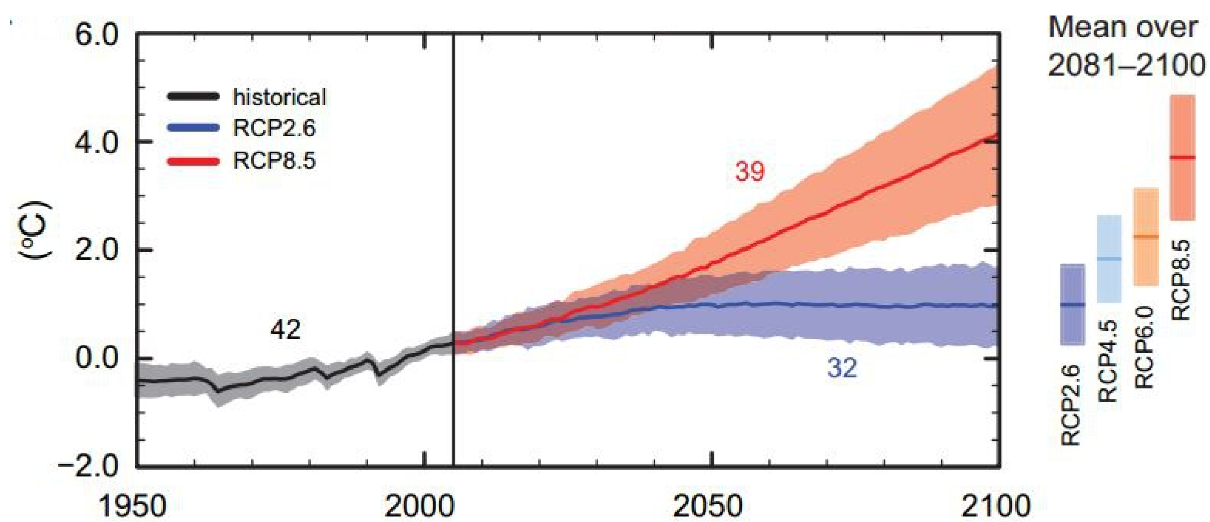

Figure 1: IPCC Surface Temperature Change Projections (From IPCC 2013 Ref. 1 Page 21)

It can be seen that if nothing is done to reduce emissions, the earth's temperature could possibly be 4 degrees Celsius (7.2°F) warmer in 2100 than it is today. This change would have immense impacts on earth systems such as the water cycle, the cryosphere, animal behavior, and the rest of the natural world [4]. As the IPCC Fifth Assessment Report states, "Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes"[1]. It is our choice as to what the earth will be like in one hundred years. If anthropogenic emissions continue to rise as they have been, we could see a big change in the earth's temperature. But, if we strive to maintain or even reduce the level of CO_2-equivalent gases in the atmosphere, we can avoid many of the harmful effects of global warming.

Greenhouse gasses (GHGs) produced by fossil fuel use and other industrial processes currently account for the largest proportion of anthropogenic greenhouse gas emissions [5]. Forty-nine giga-tons of CO_2-equivalent greenhouse gases where emitted in 2010 by human beings. A breakdown of those emissions by economic sector is presented in Figure 2.

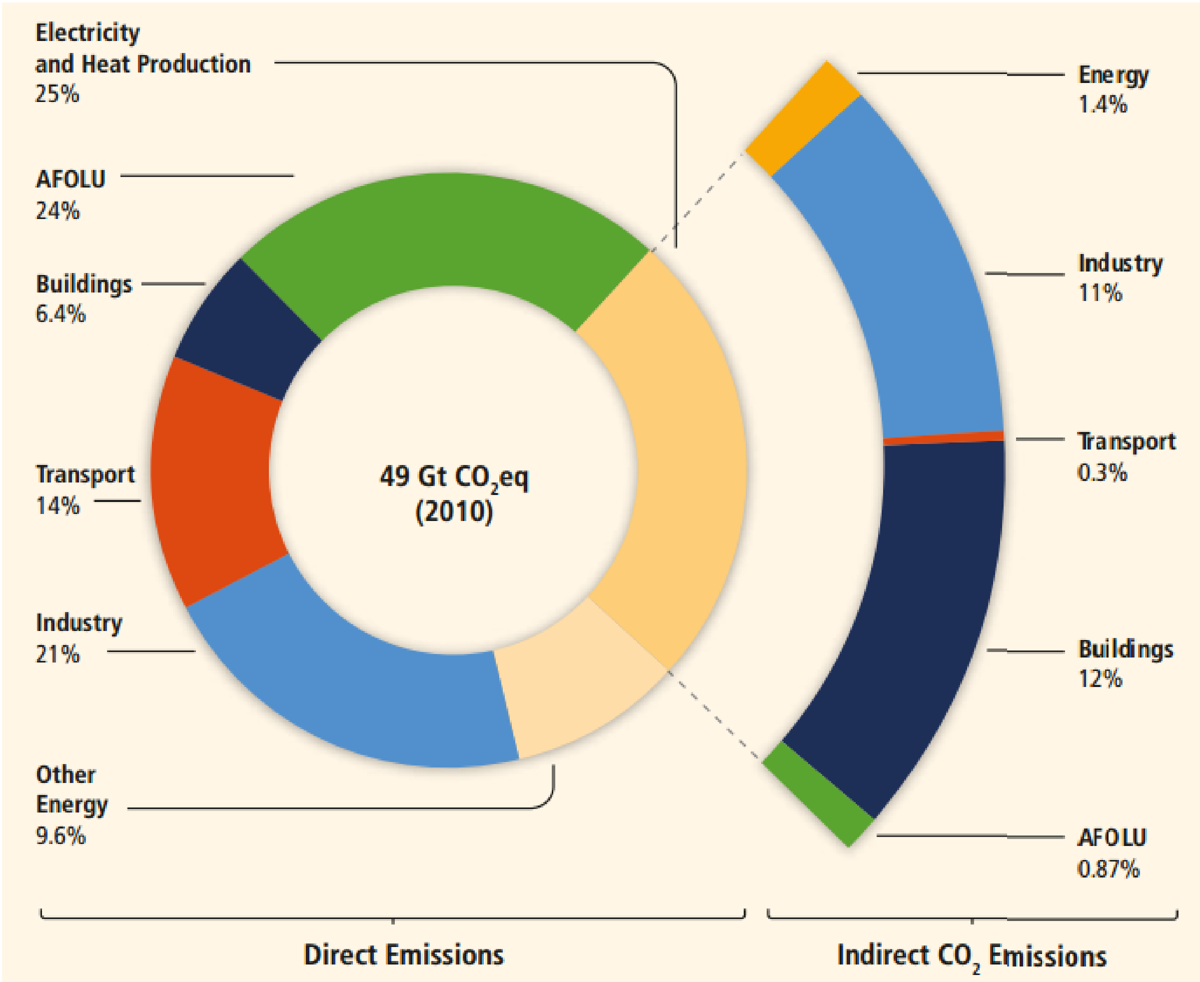

Figure 2: Anthropogenic GHG Emissions by Economic Sector (From IPCC 2013 Ref. 5 Page 9)

The electricity and heat production sector is the single largest contributor of anthropogenic greenhouse gasses at 25% or 12.25 Gt CO_2-equivalent per year. 12% of the electricity and heat produced ends up being used by buildings, and buildings themselves are accountable for 6.4% of anthropogenic GHG emissions meaning that a technology that can reduce the emissions of buildings has the potential to save up over 9 Gt CO_2-equivalent per year. In order to find a technology which suits this purpose, the current status of power utilities must be understood. This thesis uses California as a representative market, and examines the use of distributed generation to tackle this issue.

2.2 DISTRIBUTED GENERATION

California is currently powered by a centralized electricity transmission and distribution system. That is, large power plants provide electricity to a grid of interconnected transmission lines, and nearly all of the consumers of electricity within the power provider's region rely on the grid for 100% of their electricity needs. Power demands outside of the power provider's service region or individuals wishing to produce their own power may be independent of the grid, but in general every building, street light, park and facility in the service area is fed with power from the grid that was generated miles away at large centralized power plants. Economies of scale, the ability to locate large power plants near fuel sources, and a lack of competitive alternatives have all led to the centralized distribution arrangement found in California. This paradigm also exists in the rest of the United States, as well as in and most other developed countries.

Power production using small scale generators located near the end user, commonly referred to as distributed generation, has not been competitive with centralized generation for everyday power demands in recent decades. As of 2004, 99% of all distributed generation installations in America were used for back-up emergency power only [6]. A lack of reliance on distributed generation for normal use is due in part to the historical inefficiency of small scale generation technologies, but also due to complex permitting and regulatory requirements needed to construct small scale, non-utility owned power plants. Grid laws and regulations are currently set up for large regulated utilities to transmit power to the end users, not the other way around. Unless the user is a very large industrial facility requiring a lot of power on a daily basis, grim economics and the traditional regulatory structure have discouraged the use of distributed generation. However, grid congestion, a lack of transmission lines in regions of renewable resources, inherent losses in transmission, and the cost of maintaining transmission and distribution equipment are all issues that the electric grid of the future must address. A reevaluation of the current electric grid of the United States is required to ensure the reliability and availability of power going forward [7]. California is on the forefront of examining solutions to this problem, and is aggressively supporting the growth of renewable and small scale electricity generation and distribution.

2.3 CALIFORNIA'S ENERGY STANCE

California has been a leader in pollution and greenhouse gas (GHG) emissions reductions for decades. In 2005, Governor Arnold Schwarzenegger set forth Executive Order S-3-05 which sets the following greenhouse gas (GHG) emission reduction targets in California: by 2010 reduce GHG emissions to 2000 levels, by 2020 reduce GHG emissions to 1990 levels, and by 2050 reduce GHG emissions to 80% below 1990 levels. To meet the 2020 goal, California will need to reduce its carbon-dioxide-equivalent emissions to 427 million metric tons, and it will need to reduce emissions to 85 million metric tons to meet its 2050 goal [8].

In order to facilitate the installation of new renewables on a state level, the California Legislature passed Senate Bill 1078 (SB 1078) in 2002. SB 1078 establishes the Renewable Portfolio Standard (RPS) program requiring 20% of retail electricity sales to be generated by renewable energy by 2017. Subsequently, SB 107 accelerated the 20% deadline to 2010, and Executive Order S-14-08 requires 33% renewable energy by 2020. More recent California legislation dealing with the growth of renewable energy and the 33% renewable by 2020 goal is

Assembly Bill 32 (AB 32) and SB X1-2 which adopt regulations for and codify the law respectively [9]. Specific to small scale generation, Governor Jerry Brown set a goal of having 12,000 MW of renewable distributed generation in California by 2020 [10].

Between 2009 and 2012, California's renewable energy percentage has risen from 11.6% to 22%, in part due to the financial and tax incentives provided by the aforementioned legislation [10,11]. This demonstration of the immense potential of renewable energy has triggered a resurgence of support for more efficient and cleaner power production, and is turning the tide toward new ways of thinking. As "green technologies" tend to lend themselves more to small scale generation than would traditional fossil fuel technologies, the possibility of individual energy independence from the grid is promising.

California is one of the top five states leading the way for fuel cell technology in America and is currently the leader in large stationary fuel cell deployments. This is due in part to the California Public Utilities Commission's Self-Generation Incentive Program (SGIP), which provides incentives to support existing, new, and emerging distributed energy technologies [19]. The financial benefits that SGIP provides helps the new and emerging stationary fuel cell market to be competitive with more traditional power sources.

Large centralized generation is losing momentum due to regulations on once-through cooling and emissions as well as the green energy shift, but a market dominated by small-scale, privatized power production seems unrealistic in the near term, so, what is the ideal balance of power plant size and proximity to the end user for the 21st century? To help answer this question, the University of California, Irvine Medical Center (UCIMC) is working on operating its campus as a “micro-grid” and the Advanced Power and Energy Program (APEP) is studying the effect this operation has on energy cost, efficiency, and public perception.

As part of the development of the UC Irvine Medical Center micro-grid, a 1.4 MW, 200 refrigeration ton High Temperature Fuel Cell and Absorption Chiller (HTFC/AC) system has been installed and integrated into the campus electricity and chilled water utilities. If the technology is proven to be as reliable, clean, and cost effective as anticipated, market penetration of HTFC/AC systems could significantly increase and have a large, positive impact on California’s energy independence and air quality.

2.4 FUEL CELLS AND DISTRIBUTED GENERATION

Fuel cells offer the advantage of having low emissions, and certain types are well-suited for combined cooling, heating, and power applications. One major reason for the recent resurgence of distributed generation in general is the improvement in efficiencies that many alternative technologies have recently been able to garner. Stationary fuel cell technology in particular has evolved significantly over the last decade. Fuel cells now provide the advantage of being more quiet, clean, and efficient than ever.

In order for distributed generation to succeed it must have an overall positive impact on the quality of life of the user. Fuel cells and absorption chiller systems are both comparatively quiet and very clean in operation as there is no combustion associated with their operation. The fuel cell itself has no moving parts, and therefore does not produce any noise. Though the auxiliary systems such as the air blower and absorption chiller have some noise associated with them, the overall system’s noise pollution is acceptable near a campus setting. Stationary fuel cells that run on natural gas produce exceptionally low or zero pollutant emissions [12]. When fuel cells are run on pure hydrogen, they produce no emissions other than water [29].

State of the art stationary molten carbonate fuel cells can have a fuel-to-electricity conversion rate of 47% [12]. Unlike traditional power plants located miles away from the user, smaller plants that can be located very close to buildings. Molten carbonate fuel cell systems which capture and use waste heat have the potential to reach 90% overall thermodynamic efficiency [21].

2.5 FUEL CELL SYSTEMS TO OFFSET TRADITIONAL GENERATION

High temperature, stationary fuel cells can provide power to buildings, which would traditionally rely on the grid for all electricity needs. If more and more fuel cells are installed for this purpose, the electricity production capacity of the grid would see a net reduction in demand. A reduction in grid electric demand would lead to a reduction of utilization of existing electricity generation technologies. The grid operator would need to decide which power plants to reduce load from first and it is reasonable to assume that the oldest, least efficient and highest emitting plants would be the first to be affected by cut backs. It is unlikely that a reduction in grid demand would lead to a reduction in utilization of hydro-power or nuclear power as these base-load generation technologies that have low fuel prices and emissions rates [15]. In places like California where coal is all but phased out (coal comprised 7.82% of California's power mix in 2013 [12]), natural gas plants which provide 44% of the total system power [12] would be the first to see a reduction in utilization. The average natural gas plant in America produces 1135 pounds of CO_2 per MWh of electricity produced [13]. However, HTFC/AC technology deployed in California would most likely offset plants located in California. Using the 2010 versions of the Environmental Protection Agency's Emissions & Generation Resource Integrated Database (eGRID), the average natural gas plant in California emits 1,100 pounds of CO_2, 0.42 pounds of NO_x, and 0.013 pounds of SO_2 per megawatt-hour of electricity produced [14]. These numbers were calculated from the eGRID PLNT10 database by averaging emissions rates for natural gas fed electricity generating units with a capacity factor greater than 1%. The FuelCell Energy line of stationary, molten carbonate fuel cells emits 980 lb-CO_2/MWh, 0.01 lb-NO_x/MWh, and 0.0001 lb-SO_x/MWh of electricity produced.

Emission rate calculations are less straight forward for combined heating, cooling, and power applications than for power-only applications. An HTFC/AC system consisting of a 1.4 MW fuel cell and 200 refrigeration ton absorption chiller can be used as a representative case to determine the emissions savings derived from HTFC/AC systems. The 200 refrigeration tons (703.2 kW-thermal) of chilling provided from the absorption chiller of the HTFC/AC system is offsetting chilling that would otherwise come from an electric chiller. If the electric chiller being offset is assumed to have a coefficient of performance of 3.4, then the HTFC/AC technology is offsetting 206.8 kW of electricity from the grid that would have gone toward powering the electric chiller (703.2 kW / 3.4). Therefore, the HTFC/AC emissions rates are based on an output of 1.607 MW-electric (MW_e).

Table 1: Emissions

	lb-CO2/MWhe	lb-NOx/MWhe	lb-SOx/MWhe
U.S. Average NG Plant [13]	1,135	1.7	0.1
California Average NG Plant [14]	1,100	0.42	0.013
FuelCell Energy DFC Line of MCFCs [17]	980	0.01	0.0001
HTFC/AC Technology [17] [18]	854	0.0087	0.00009

Emissions values summarized in Table 1 show that even in a state such as California where strict emissions standards are already in place, GHG and criteria pollutant emissions can be significantly reduced by the utilization of HTFC/AC technology.

2.6 COOLING AND HEATING IN SOUTHERN CALIFORNIA

Clean and affordable electricity is of high value to any industrialized society, regardless of geographic location. However, the value of heating versus cooling is highly dependent upon the climate in the particular region. Populations in warm and arid climates such as southern California typically value cooling more than heating. For example, the California Commercial End-use Survey (CEUS) published in March 2006 is a survey of electricity and natural gas use in commercial buildings in California. It includes results from various utilities in California, including Southern California Edison (SCE). The SCE service territory encompasses 50,000 square miles and includes portions or all of Mono, Inyo, Tulare, San Bernardino, Kern, Santa

Barbara, Ventura, Los Angeles, Orange, and Riverside counties. The CEUS reports that for the SCE service territory, 144.11×10^6 therms of natural gas and 357 GWh of electricity were used for heating commercial buildings in one year, equaling a total of 4,580 GWh of end-use energy. The CEUS also reports that for the same territory, 6.58×10^6 therms of natural gas and 4,939 GWh of electricity were used in the same year for cooling commercial buildings, equaling a total of 5,132 GWh of end-use energy [22]. Therefore, in the warm and arid climate of the SCE service territory, 12% more end-use energy is used for cooling as opposed to heating of commercial buildings. This makes the market for combined cooling and power systems larger than that of combined heating and power systems. But the question remains as to which option is better for the individual investor.

From the CEUS report, 96% of the energy for commercial building cooling comes from electricity systems and 92% of energy for heating comes from natural gas systems. If it is assumed that the electricity rate is \$0.12/kWh and the natural gas price is \$5/MMBtu or \$0.07/kWh, then the cost of cooling a building is \$0.118/kWh (96% x \$0.12/kWh + 4% x \$0.07/kWh). On the other hand, the cost of heating a building is \$0.074/kWh (8% x \$0.12/kWh + 92% x \$0.07/kWh). Therefore, an investor can expect to save roughly 4.4 cents per kilowatt-hour more by offsetting commercial building cooling loads rather than heating loads in the SCE service territory. The SCE service territory can be thought of as a representative warm, arid climate and the potential for combined cooling and power applications in other parts of the world with similar climates is promising. The key will be ensuring that whatever system is used to meet these needs will be small scale enough to be distributed near the end user and will also produce less pollution and greenhouse gases emissions than what is currently being used. For this reason, High Temperature Fuel Cell and Absorption Chiller (HTFC/AC) systems have a promising future.

2.7 HTFC/AC RESEARCH AT APEP

The Advanced Power and Energy Program (APEP) has been investigating the physics and economics of High Temperature Fuel Cell and Absorption Chiller (HTFC/AC) systems since 2003. Three graduate students have written their Master's Degree Theses on the topic, they include Pere Margalef Valldeperez's "The Integration of a High Temperature Fuel Cell and Absorption Chiller into a Generic Building" (Margalef), Sarah Marie Martz's "Modeling and Integration of a Combined Cooling, Heating and Power System with a High Temperature Fuel Cell and Absorption Chiller," (Martz), and Kyle S. Hosford's "Design and Economic Potential of an Integrated High-Temperature Fuel Cell and Absorption Chiller Combined Cooling, Heat, and Power System" (Hosford).

Margalef modeled various fuel cell and absorption chiller combinations and found that the optimal coupling for a 300kW molten carbonate fuel cell is a 40 refrigeration ton, double effect absorption chiller. He analyzed the mismatch between exhaust gas temperature and mass flow rate coming out of the fuel cell compared to what the absorption chiller requires. He found that the issue can be resolved by cooling and mixing the fuel cell exhaust gases with a fraction of the chiller exhaust gases.

Martz analyzed various buildings to create generic building load data sets which provide electricity, heating, and cooling loads over an entire year. She created a steady state thermodynamic model in Aspen Plus® and a dynamic model in Matlab Simulink® of a double effect 40 refrigeration ton absorption chiller. The exhaust condition mismatch between the fuel cell exit and absorption chiller inlet were again analyzed. Martz looked at various ways of reducing the temperature of the exhaust entering the absorption chiller and determined that the preferred method was diverting unnecessary exhaust from the chiller and sending it to a heat recovery unit. She also used the transient model to determine that the absorption chiller was capable of load following throughout the day.

Hosford used the optimized electricity to cooling tonnage ratio developed by Margalef to determine that a 1.4MW fuel cell couples well with a 200 refrigeration ton absorption chiller, and a 2.8MW fuel cell couples well with a 400 refrigeration ton absorption chiller. This gives an absorption chiller target design for each of the three HTFCs in FuelCell Energy's fleet of molten carbonate fuel cells. Hosford then collaborated with Lori Shell of Empowered Energy to use these three size combinations to create an economic analysis tool.

This thesis work carries on the evolution of HTFC/AC research at APEP. The economic tools developed by Hosford and Empowered Energy are used to characterize the economic behavior of HTFC/AC systems in a broad and extensive manner so as to better inform the market and the public of the viability of HTFC/AC systems. A full scale prototype is deployed at the University of California, Irvine Medical Center (UCIMC). It is highly instrumented to provide data for future research efforts to verify and improve APEP's HTFC/AC thermodynamic and economic simulations.

2.8 HTFC/AC INSTALLATION AT UC IRVINE MEDICAL CENTER

A Distributed Generation (DG) solution that provides electricity and cooling to buildings but contributes relatively little to the growing global warming issue and the pollution that is plaguing many of California's metropolitan areas is needed in order to support the self-generation goals of SB-970 and the climate change mitigation goals of AB-32. This technology exists in the form of High Temperature Fuel Cell and Absorption Chiller (HTFC/AC) systems, but will require a successful, full scale demonstration in order to encourage the DG market and increase HTFC/AC penetration to a level that can have significant impacts on California's energy portfolio.

The Advanced Power and Energy Program is assisting the University of California, Irvine Medical Center (UCIMC) in deploying an integrated high-temperature fuel cell and absorption chiller (HTFC/AC) system. The HTFC/AC system will provide UCIMC's Douglas Hospital with 1.4 MW of electricity and over 200 refrigeration tons of cooling (800 kW) while serving as a technology transfer showcase in order to enable the market.

The fuel cell chosen for this application is FuelCell Energy's DFC1500. This molten carbonate fuel cell is designed to operate as a base load electricity generator and has the benefit of producing high quality waste heat. An absorption chiller is used in this application to capture the high quality waste heat from the fuel cell and convert it into cooling for the hydronic air conditioning system of the Douglas Hospital. The integrated system energy flow is depicted in Figure 3.

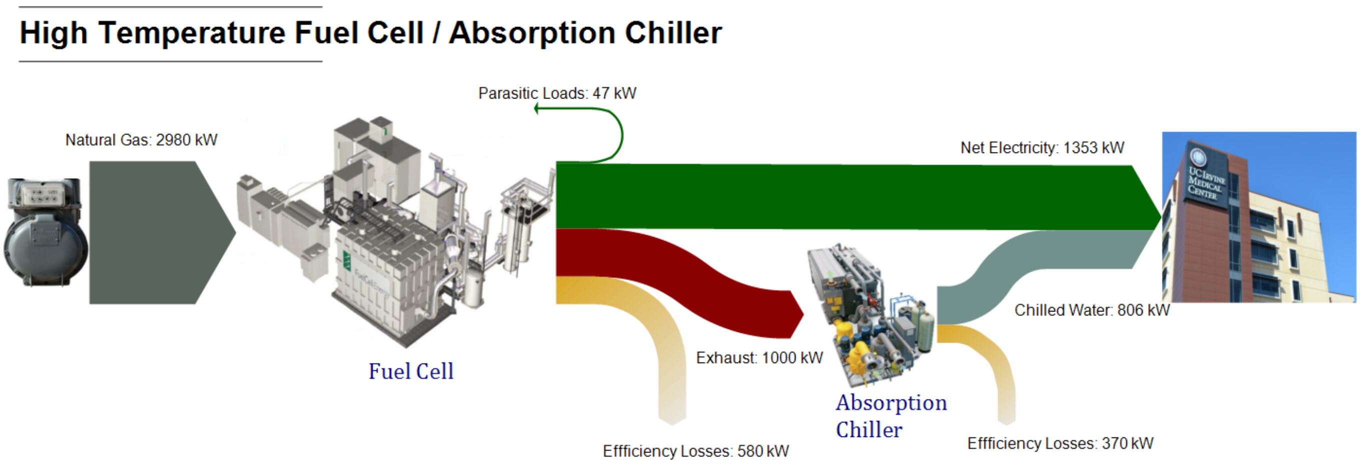

Figure 3: Sankey Diagram of HTFC/AC System at UCIMC

When compared to electricity generated from a typical combined cycle natural gas plant, pollutant emissions are reduced by over 99% and greenhouse gas emissions are reduced by more than 40%. The demonstration was strategically launched in the South Coast Air Basin to address the regional need for clean, affordable power as well as cooling for hydronic air conditioning systems. Demonstration of the viability of this technology in a showcase environment will engage the distributed generation market and encourage future deployments of HTFC/AC CCHP systems in California.

2.8.1 FUEL CELL

FuelCell Energy publishes an electric efficiency of 47±2% for its line of stationary, molten carbonate fuel cells (MCFCs) and an associate greenhouse gas emissions rate of 980 lb-CO_2/MWh. The product line consists of the DFC300, DFC1500 and DFC3000 which are 300 kilo-Watt (kW), 1.4 Mega-Watt (MW), and 2.8 MW versions of a high temperature, natural gas fed fuel cell. The electrical efficiency of a fuel cell is based on many factors which affect both the electrochemistry within the anode, cathode, and electrolyte as well as the overall system design external to the fuel cell stacks.

Electrochemistry, or the conversion of chemical to electrical energy is the fundamental process behind all fuel cells. While traditional heat driven electric generators require an intermediate mechanical process to convert heat to electricity, fuel cells convert a chemical potential directly into electricity. This characteristic of direct conversion offers an inherent efficiency advantage in fuel cells, but electrochemistry remains subject to entropic caution as does any other electricity generating process.

The reversible efficiency of a fuel cell is the ratio of the change in Gibbs free energy to the change in enthalpy of the reaction taking place between the anode and cathode. At room temperature and pressure the highest reversible efficiency that can be achieved by an H_2-O_2 fuel cell at room temperature and pressure is 83% [23]. However, unlike traditional Carnot type engines, the reversible efficiency of a fuel cell decreases with temperature. Also, different losses associated with activation, ohmic, and concentration polarization tends to inhibit the reaction within the fuel cell and in turn degrade its performance. The parasitic loads associated with the large balance of plant that is required for MCFCs will reduce the system's efficiency as well.

For a high temperature molten carbonate fuel cell, a published electrical efficiency of 47% is in line with the industry norm [21]. The electrical efficiency of the fuel cell being installed at the UCI Medical Center will be continuously monitored and compared to the expected value.

2.8.2 ABSORPTION CHILLER

BROAD U.S.A. Incorporated quotes a Coefficient of Performance (COP) of 1.28 for its direct exhaust fired, double effect, lithium bromide absorption chiller when it operates on 18,325 pounds per hour of 712^{o}F exhaust gas [18]. This means that for every 1 thermal kW the absorption chiller captures from the exhaust gas, 1.28 thermal kW of chilling goes into the chilled water stream. Typically triple effect absorption chillers reach COPs of around 1.2 and a COP of 1.0 is typical for double effect absorption chillers [24]. The actual performance of the absorption chiller installed at UCIMC will be measured by recording the flow and change in temperature of both the chilled water and exhaust steams across the absorption chiller.

If the absorption chiller were capable of operating with a COP of 1.28 while capturing heat from the entire exhaust stream, the chilling delivered to the chilled water system could potentially be 1000 kW x 1.28 = 1280 kW. Due to material and design constraints of the off-the-shelf absorption chiller, a large amount of exhaust is bypassed around the absorption chiller thus reducing the system's potential. Under best case conditions the chiller manufacturer quotes a chilling output of 806 kW for the configuration at UCIMC. Therefore, the manufacturer is assuming the absorption chiller can capture only 630 kW of thermal energy from the 1000 kW available from the exhaust stream.

2.8.3 PARASITIC LOADS

The HTFC/AC system at UCIMC has a large mechanical balance of plant with various pumps and fans that act as parasitic loads on the system. Major contributors to the overall parasitic load of the system include the fuel cell air blower, cooling tower fans, chilled water pump, cooling water pump, and absorption chiller solution pumps. The individual loads from each of these pieces of equipment are shown in Figure 4.

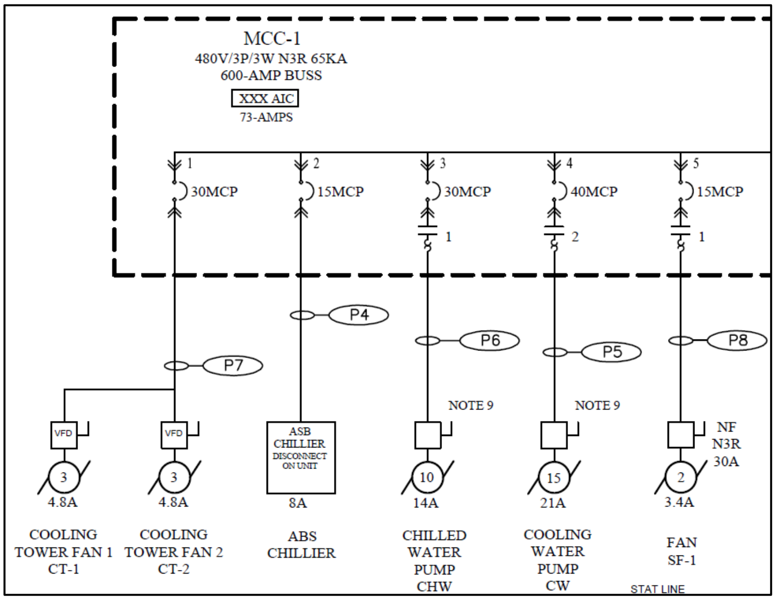

Figure 4: One Line Diagram of Parasitic Loads

The parasitic load is expected to total 47 kW and will be monitored during plant operation. Each of the motors serving pumps and fans will be monitored directly using current transformers. The absorption chiller loads will be monitored indirectly by subtracting the pump and fan loads from the total MCC power draw.

2.8.4 OVERALL EFFICIENCY

In combined heat and power application in which the high quality exhaust heat is captured and used to produce a useful product, MCFC systems could theoretically achieve an overall efficiency of close to 90% [3]. For the installation at UCIMC, the expected efficiency can be calculated as follows given the expected performance shown in the Sankey diagram of Figure 3.

$$\eta = 100\ x\ \frac{Net\ Work\ Out}{Energy\ In} = \frac{1400kW - 47kW + 806kW}{2980kW} = 72.45\%$$

2.8.5 BENEFITS

Furthering the understanding of economic, thermodynamic and operational characteristics of HTFC/AC systems will serve to advance the market-readiness of the technology, while industrial deployment of the system will encourage the market and pave the way for future installations. Increased market penetration of HTFC/AC systems will reduce pollution and greenhouse gasses, while increasing distributed generation capacity in California thereby supporting the goals of AB-32 and SB-970. Other benefits include:

- Lower Costs: HTFC/AC systems like the one being deployed at the UC Irvine Medical Center qualify for California's Self Generation Initiative Program (SGIP) and have the potential to reduce electricity costs for ratepayers. Technology adoption on a large scale will help California meet its AB-32 emissions goals and will help owners avoid the costs associated with carbon emissions and electricity production.
- Greater Reliability: This technology lends itself nicely to a micro-grid system in which it can offset the need for conventionally generated power and/or provide backup and emergency power.
- Increase Safety: Fuel cell systems have few moving parts and are known for having a low noise signature [29].

- Economic Development: Growth of the DG market in the form of MW scale, base load fuel cells has the potential to create maintenance, engineering, sales, manufacturing, and construction jobs in California.
- Environment Benefits: Greenhouse gas (CO_2) emissions associated with a 1.4 MW, 200 refrigeration ton HTFC/AC system are 1,372 lb-CO_2/hr compared to 1,767 lb-CO_2/hr from the same amount of electricity and cooling provided by a typical natural gas power plant in California and an electric chiller with a COP of 3.4 [14]. This equates to a savings of 188 lb-CO_2/MWh-combined where MWh-combined represents both electric and thermal production [14, 18] (See Appendix B for Calculation). If all of the electricity and cooling requirements for commercial buildings in the Southern California Edison service territory were served by HTFC/AC technology, CO_2 emissions would decrease by 3,272 metric tons per year (29,321,000 MWh [22] x 246 lb-CO_2/MWh ÷ 2204.6 lb/ton). If all of California's electricity and cooling requirements for commercial buildings were served by HTFC/AC technology, CO_2 emissions would decrease by 7.48 million metric tons per year (67,077,000 MWh [22] x 246 lb-CO_2/MWh ÷ 2204.6 lb/ton). This reduction would account for 2.1% of the emissions reductions required in California between 2020 and 2050 under Executive Order S-3-05 [8].
- Public Health: Wide scale acceptance of this technology would reduce emissions from traditional forms of power generation. Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2) emissions from HTFC/AC systems are 0.0087 and 0.00009 lb/MWh respectively from the HTFC/AC system [17, 18] while a typical natural gas power

plant in California emits 0.42 lb/MWh of nitrogen oxides and 0.013 lb/MWh of sulfur oxides [14]. Therefore, HTFC/AC systems in California reduce criteria pollutant emissions by 0.4113 lb-NO_x/MWh_e and 0.0129 lb-SO_x/MWh_e. If the electricity generated to serve all of the commercial building loads reported for the Southern California Edison (SCE) service territory in the California End-use Survey were generated by HTFC/Chiller technology, 5,470 metric tons of NO_x (29,321,000 MWh [22] x 0.4113 lb-NO_x/MWh_e ÷ 2204.6 lb/ton) and 171 metric tons of SO_x (29,321,000 MWh [22] x 0.0129 lb-NO_x/MWh_e ÷ 2204.6 lb/ton) would be avoided each year. To put this into perspective, the South Coast Air Quality Management District (SCAQMD) projects that in order for the South Coast Air Basin to meet the EPA standard for 8 hour ozone levels, it must reduce its NO_x emission rate by a total of 320 metric tons per day [20]. To meet this goal, the SCAQMD is expecting a NO_X emission reduction from aircraft of about 15 metric tons per day, a rate equivalent to the emissions reductions derived from using HTFC/AC technology to serve all of the commercial building loads in the SCE service territory.

- Consumer Appeal: The demonstration of this technology will prove that clean energy can be deployed near the end use customer in a reliable, affordable, and aesthetically acceptable fashion.

2.9 SUMMARY

HTFC/AC technology has the potential to revolutionize California's energy infrastructure by providing distributed power and cooling to individual commercial buildings and thereby offset electricity production for traditional, grid-reliant sources. Wide-spread growth of HTFC/AC technology would yield significant reductions in criteria pollutant and Greenhouse Gas emissions. This thesis investigates the current and future economic climate for HTFC/AC technology in order to assess its competitiveness with existing technology and establishes a technology transfer platform in order to inform the public about the real-world potential of HTFC/AC technology.

3 APPROACH

The goal of this thesis is to enhance the distributed generation market potential of high temperature fuel cell and absorption chiller systems through rigorous modeling of the economic attributes of HTFC/AC technology in combination with a robust demonstration. To achieve this goal, the following tasks were addressed.

Task 1: Analyze the financial viability of megawatt-class high temperature fuel cell and absorption chiller systems.

The economics of deploying high temperature fuel cell and absorption chiller (HTFC/AC) systems in a distributed generation arrangement were evaluated using an updated version of the integrated economic and technical model described in Hosford, 2013 [27]. The model was tailored to simulate the integration of FuelCell Energy's class of molten carbonate fuel cells with BROAD U.S.A.'s class of exhaust fired lithium bromide absorption chillers. Simulations were run to (1) characterize the optimal HTFC/AC system equipment portfolio for different building types, (2) analyze the economic impact of different financial and ownership conditions, (3) characterize equipment costs associated with different HTFC/AC portfolios, and (4) statistically distinguish the relative importance of key economic and engineering assumptions built into the model.

Task 2: Create a technology transfer platform for high temperature fuel cell and absorption chiller systems.

A technology transfer environment is required to maximize knowledge transfer to students, educators, key decision makers, developers and other influential members of the public. A dedicated showcase room, project website, and installation scheme are needed to present system technology and operating information in an attractive and informative manner suitable for public consumption. Real-time measurements collected from an installed system are required as key inputs to the technical content of the showcase experience.

An HTFC/AC installation at the University of California, Irvine Medical Center (UCIMC) is selected to provide this technology transfer environment and thereby enable the market by demonstrating a real-world application of the technology and bolstering confidence in system models and performance ratings.

The HTFC/AC system is designed to be highly instrumented in order to provide inputs to the showcase experience as well as for model and performance verification in order to encourage the market. A comprehensive data acquisition portfolio is created in collaboration with the third party provider. Measurements selected include key process parameters which will be used in the future to verify the economic model developed in Task 1 of this thesis, the engineering models developed by Martz [28], and the published performance ratings of the individual pieces of equipment. A custom data acquisition platform is created in LabVIEW® which retrieves and stores the real-time data from the fuel cell site. The data retrieved from the HTFC/AC installation are used as a key component of the technology transfer goal of the project.

4 TASK 1 RESULTS

Task 1: Analyze the financial viability of megawatt-class high temperature fuel cell and absorption chiller systems.

An economics model was jointly developed by the Advanced Power and Energy Program and Empowered Energy to calculate the costs associated with different High Temperature Fuel Cell and Absorption Chiller (HTFC/AC) installations. Robert Flores of the Advanced Power and Energy Program created a suite of Matlab® codes which simulate the operation of a HTFC/AC system as a function of building load demand. The output of this engineering model is a "Master Matrix" of energy flows from the various pieces of equipment specified by the user. Dr. Lori Schell of Empowered Energy developed an economic analysis code which translates the energy flow outputs of the Master Matrix into levelized costs of electricity. Kyle Hosford of the Advanced Power and Energy Program (APEP) created a graphical user interface which coordinates communication between the economic code and engineering codes. A description of the integrated HTFC/AC Economic Model prior to revision for this thesis is presented in Chapter 7 of Hosford, 2013 [27].

The model was updated to accurately reflect the operation of three sizes of stationary, molten carbonate fuel cells in conjunction with double effect absorption chillers, heat recovery units, electric chillers, natural gas boilers, thermal energy storage tanks, and grid electricity to serve the power, heating, and cooling loads of different building types. Section 4.2 characterizes the optimal HTFC/AC system equipment portfolio for different building types, Section 4.3 analyzes the economic impact of different financial and ownership conditions, Section 4.4 characterizes equipment costs associated with different portfolios, and Sections 4.5.4 and 0 statistically distinguish the relative importance of different economic and engineering assumptions built into the model.

4.1 ECONOMIC MODEL

4.1.1 MODEL INPUTS

The Economic Model described in Hosford, 2013 [27] was updated substantially in order to evaluate the financial impact of deploying HTFC/AC systems with various equipment portfolios and input assumptions at buildings with unique load profiles. First the model was modified by replacing the Graphical User Interface with a "Run" code entitled HTFC_Chiller_Econ_Run.m. This script contains all the model inputs formally found in the GUI, along with a few new global variables.

Financial and scenario specific inputs are set individually, with the commonly manipulated input values contained in the "input_matrix." Manual input of the various parameters is required in the Run code. Unless otherwise noted, the default values shown in Table 2 were used in the analysis contained in Section 4 of this thesis. Any inputs used to get results shown in Section 4 that are not set to the default value are explicitly noted.

Table 2: Default Code Inputs

Parameter	Default Value	Description
Scenario_type	1	Cost calculations are based on imported Master Matrix workbook
Fc_baseload_eff	47	Fuel cell fuel to electricity efficiency at full load
COP	1.28	Absorption Chiller coefficient of performance
Fixed O&M	200	$ per rated kW per year to operate and maintain the system
Variable O&M	0.21	$/MW to operate and maintain the system
Annual Starts	4	Number of times the fuel cell is started per year
Start-Up Fuel per Start	10	MMBtu/MWh
Stack Life	5	Years between stack replacements
Economic Life	20	Economic life of the project in years
CO2_toggle	1	CO_2 tax rate starts at a flat $/ton rate (CO2_ton_flat) and increases with inflation
CO2_ton_flat	20	CO_2 tax rate for year one in $/short ton CO_2
Ng_cec_forecast	0	Natural gas price starts at a flat rate (ng_start_price) and increases with inflation
Ng_start_price	5	Natural gas rate for year one in $/MMBtu
Elec_import_forecast	0	Electricity import price starts at a flat rate (elec_import_price) and increases with inflation.
Elec_import_price	120	Electricity import rate for year one in $/MWh
Export_rate	30	The owner is compensated at this rate plus inflation for electricity exported to the grid
Elec_chiller_cop	3.4	Electric chiller coefficient of performance
Elec_chiller_sizing	Tailoring	Electric chiller is sized by the program to meet a certain percentage of the chilling demand not met by the absorption chiller
Elec_chiller_percent_of_max	100	In the tailoring strategy, the electric chiller is sized by the program to meet this percentage of cooling not met by other equipment
Boiler_eff	80/100	Natural gas boiler efficiency
Boiler_sizing	Tailoring	Natural gas boiler is sized by the program to meet a certain percentage of the heating demand not met by any other equipment
Boiler_percent_of_max	100	In the tailoring strategy, the natural gas boiler is sized by the program to meet this percentage of heating not met by other equipment

Own_type	1	Merchant owned system
Tax_loss_carryover_toggle	0	Tax losses are recognized in the year they occur
Equity_percent	33/100	Percent of the total assets financed by shareholders or investors
Return_rate	13.25/100	Required rate of return to the shareholders or investors on the percent financed by equity
Loan_interest	5.91/100	Interest rate on the debt owed by the owner to the bank
Apply_beitc	0	Business energy investment tax credits are not applied
tes_size	200	Maximum ton-hours of cooling that can be stored in the TES
Tes_discharge_rate	80	Rate of recoverable cooling from TES is limited to this refrigeration tonnage
Tes_storage_eff	80/100	Percent of cooling stored in the TES that is available for later dispatch

The model simulates FuelCell Energy's DFC line of molten carbonate fuel cells, which range from 300 kW to 2.8 MW capacities (Ref. Section 2.8.1). The published thermal-to-electric efficiency of the fuel cell line is 47%. Capital (over-night construction) costs of $3600, $3300, and $3000/kW were applied to the 300 kW, 1.4 MW, and 2.8 MW fuel cells, respectively.

The absorption chiller modeled in the economics code is a direct exhaust fired BROAD U.S.A. double effect lithium bromide chiller (Ref. Section 2.8.2). The rated coefficient of performance (COP) of the BROAD line of absorption chillers is 1.28. Capital (over-night construction) costs of $600, $570, and $540/ton were applied to the 40, 200, and 400 refrigeration ton absorption chillers, respectively.

Parasitic loads are simplistically modelled in the economics code as a set percentage of fuel cell output. It is very difficult to estimate the electricity required to power all of the auxiliary loads of an HTFC/AC system because they will vary with each installation and operating conditions. For example, the size of pump that is installed to supply the building with chilled water will be a function of the size and length of piping selected, as well as the flow and temperature requirements of the system. The 1.4 MW HTFC/AC system being installed at the University of California, Irvine Medical Center has a name-plate parasitic load of 47 kW which is 3.36% of its rated output. A conservative parasitic power fraction of 10% is assumed in typical model runs to account for degradation over time and variations in design and operating conditions.

CO_2 price is the \$/short-ton-CO_2 value assigned to any CO_2 produced to serve the loads of the building. Emissions could come from the fuel cell, the natural gas boiler, or from the grid when it provides imported electricity to the building or electric chiller. The CO_2 price in California is currently \$13/ton [26]. The California Energy Commission's Cost of Generation Model 3.62 predicts that the price of CO_2 will rise to \$135/ton in 25 years. A CO_2 rate of \$20/ton is generally assumed in order for the evaluations to be applicable to near-term, future HTFC/AC installations.

The rate for natural gas purchased for a small commercial building through the Southern California Gas Company in January 1, 2015 is \$6.32/MMBtu, down 14.6% from December 1, 2014 [30]. A natural gas price of \$5/MMBtu is typically assumed in this thesis in order for the evaluations to reflect lower prices in the near-term future.

The average electricity price for the University of California, Irvine Medical Center was \$130/MWh in 2014 [31]. An electricity import price of \$120/MWh is assumed in this thesis in order for the HTFC/AC levelized cost of electricity comparisons to be conservative relative to the competing scenario.

The rate that a utility is willing to pay for electricity exported to the grid by a distributed generation unit depends upon numerous factors including utility policies, currently available infrastructure, grid capacities in the region, and legal issues. Electricity export rates are generally assumed to be \$30/MWh in this thesis in order to provide a conservative analysis. For reference, the net energy metering surplus compensation rate for Southern California Edison was \$45.12/MWh in March 2015.[32]

For a detailed description of the other cost parameters in refer to Hosford, 2013 [27].

4.1.2 MODEL EXECUTION CHANGES

Three for-loops were included in the Run file to allow the user to analyze different input assumptions, building types, and equipment portfolios at the same time.

The first loop steps through the inputs_matix which is a compilation of input vectors, each of which is sufficient to set the scenario for a particular code run. The loop allows the user to quickly and efficiently analyze different input assumptions. The following are inputs to the input vector: fuel cell base load efficiency (%), absorption chiller coefficient of performance, parasitic power fraction (%), CO_2 tax rate at year one (\$/ton), natural gas price at year one (\$/MMBtu), electricity import rate at year one (\$/MWh), electricity export rate at year one (\$/MWh), and ownership type. Ownership type one (1) represents a merchant owned system, ownership type two (2) represents an investor owned utility, and ownership type three (3) represents a publicly owned utility.

The second loop is embedded in the first, and steps through the test_buildings vector which represents each of the building types being analyzed. A one (1) in the vector will reference the Long Beach Veteran's Affairs Hospital load profile, a two (2) will reference the Multipurpose Science and Technology Building load profile, a three (3) will reference the South Coast Air Quality Management District load profile, and a four (4), a five (5) and a six (6) will reference the fictitious building load profiles created to match the 300 kW, 1.4 MW and 2.8 MW HTFC/AC portfolios respectively. The user can specify as many building types as desired, and the program will run each of the specified equipment portfolios and input conditions on each of the buildings selected.

The third loop is embedded in the second, and is based on the test_portfolios matrix which is a compilation of equip_select vectors with each row representing a single equipment portfolio. The loop will run the engineering and cost codes for each equipment portfolio (equip_select) vector in the matrix. Each digit in the equip_select vector is a binary input representing the presence or absence of equipment in the portfolio. A one (1) in the first column represents the inclusion of a 300 kW fuel cell, while a (0) in the first column means there is no 300 kW fuel cell in the portfolio. Each input to the equip_select vector is shown in Table 3. For example, an equip_select vector of [0 1 0 0 1 0 1 1 0 1 1] represents a 1.4 MW fuel cell with a 200 refrigeration-ton absorption chiller, a natural gas boiler, an electric chiller, a heat recovery unit and grid imports and exports.

Table 3: Vector Inputs for Portfolio Selection

1	2	3	4	5	6	7	8	9	10	11
300 kW Fuel Cell	1.4 MW Fuel Cell	2.8 MW Fuel Cell	40 ton Absorption	200 ton Absorption	400 ton Absorption	Natural Gas Boiler	Electric Chiller	Thermal Energy	Heat Recovery Unit	Electricity Imports

The model is designed to analyze the energy flows and economics of any combination of equipment selected from the equip_select vector as long as no more than one size fuel cell and one size absorption chiller is selected. Based on the results of Hosford and Margalef, this analysis always couples the 300 kW fuel cell with the 40 ton chiller, the 1.4 MW fuel cell with the 200 ton chiller, and the 2.8 MW fuel cell with the 400 ton chiller.

The last modification to the execution code was to update the model outputs by including the compilation of a results matrix. Each time the equipment loop executes the mechanical and economic codes, relevant model inputs and outputs are sent to a spreadsheet. Once the program steps through all of the for-loops, the results matrix is fully populated with input parameters, equipment selection, building selection, and major model outputs for each run. The bar graph developed by Hosford as the output of the Graphical User Interface remains a part of the economic code, but it is modified slightly to display parameters such as portfolio size, building name, CO_2 production and water usage.

4.1.3 ENGINEERING AND ECONOMIC MODEL ENHANCEMENTS

The flexibility of excluding a heat recovery unit was added to the engineering dispatch code. Along with that, several small adjustments were made to the suite of engineering codes in order to tune the model to the characteristics of FuelCell Energy's line of molten carbonate fuel cells. The fuel cell's natural gas consumption rate, CO_2 production rate, and water usage rate were each updated to match the manufacturer specified values. The emissions and water usage calculations were updated to follow fuel consumption rates of the fuel cell.

Also, a coefficient of performance was included in the absorption chiller model. New global variables for fuel cell efficiency and absorption chiller coefficient of performance were created in the Run code and referenced in the engineering codes. The code responsible for simulating fuel cell operation (DFC_Lookup.m) previously simulated dynamic responses to load changes by multiplying the base load efficiency by a normalized efficiency curve based on the fuel cell's load fraction. Since these analyses always assume base load operation of the fuel cell, the normalized efficiency curve was removed to reduce computation time.

Few changes were required in the economic model. The only significant adjustments were including inflation escalation in the calculation of CO_2 taxes and electricity import and export rates.

4.1.4 SCENARIOS EVALUATED

The model was executed numerous times to evaluate various equipment portfolios and scenarios. Appendix A provides a comprehensive list of the model runs that were executed to create the results in Sections 4.2 and 4.3.

In each of the scenarios evaluated in this thesis, the operating life of the system is assumed to be 20 years. The fuel cell is always run at base-load capacity, and any electricity produced by the fuel cell that is not utilized by the building is exported to the grid. It is important to note that in cases where the integrated HTFC/AC system is a net exporter of electricity, the fuel cell system is compensated at $30/MWh for those electricity exports, making it difficult to compare its LCOE with the LCOE of the competing system directly.

Three different building load profiles were evaluated herein; a generic office building, a hospital, and a small office building. The Multipurpose Science and Technology Building (MSTB) is a generic office building on the main campus of UCI that is used for classrooms, laboratories, and offices. The Long Beach Veteran's Affairs Hospital (LBVA) is a 237-bed comprehensive tertiary care facility. The South Coast Air Quality Management District building (SCAQMD) is a relatively small office building with low power demands.

4.1.5 INTERPRETING MODEL RESULTS

The actual annual cost of operating a power plant changes throughout the year. Levelized cost refers to the constant value that is equivalent to the average annual total cost, over the life of the asset, incorporating standard present value discounts. Levelized cost of electricity, commonly referred to by its acronym LCOE, is a metric used in this and other economic studies to compare the cost of generation from different power sources. LCOE is a composite of numerous inputs including both fixed and variable costs that are all levelized for ease of compilation and comparison. Fixed costs such as capital, financing, insurance, Ad Valorem, and fixed operating and maintenance are included as well as variable costs associated with fuel and variable operating and maintenance (O&M). Capital encompasses all of the construction costs including land purchase, permitting, interconnection, original equipment, etc. Financing costs cover the debt and equity of the project. Insurance covers the premium for the power plant itself and is based on a first-year estimate which escalates over time. Ad Valorem covers the annual property tax of the power plant. Fixed O&M includes staffing, overhead, equipment, and other annual costs associated with the plant regardless of how much it operates. Variable O&M changes as a function of the operation of the power plant and includes costs for yearly maintenance, overhauls, water supply and other consumable. And finally, fuel costs include the amount spent on fuel for both operation and start up. All costs are reported on a present value basis.

The remainder of Section 4 details the results from analyses performed using the economic model to simulate various HTFC/AC installation scenarios. The primary output of the economic model is a chart with bar graphs representing the individual levelized cost of energy (LCOE) for each piece of equipment in the portfolio. The weighted-average LCOE for the portfolio of equipment is displayed in the legend on the right. The portfolio LCOE represents the cost per unit energy that must be returned to the owner to recuperate all expenses, including debt interest and equity return, over assumed operating life of the system. It is the break-even value of the project.

In the results chart, each piece of equipment has three parallel vertical bars representing total LCOE (left), non-renewable LCOE (middle), and renewable LCOE (right). The bars are split horizontally into costs categories associated with each piece of equipment: fuel, transmission, variable operation and maintenance, CO_2 tax, fixed operation and maintenance, overnight installation cost, net equity, debt, ad valorem tax, state tax, and federal tax. If a piece of equipment has a very low capacity factor (i.e., it sits idle most of the time), it will have a very large LCOE. This can be the case even if the actual cost of the equipment is low, as the LCOE calculation is on a per kW basis. To avoid skewing the plots to fully display these outliers that do not contribute very significantly to the portfolio LCOE, the plots are designed to maintain a constant height.

The text box in the lower right hand corner displays numerical values for the portfolio levelized cost of electricity (Portfolio LCOE), the total amount of CO_2 emitted from the equipment portfolio and from the grid for any electricity that was imported (Total CO_2), and the amount of water used by the equipment portfolio (Water).

4.2 CHARACTERIZING HTFC/AC PORTFOLIOS FOR BUILDINGS

4.2.1 MULTIPURPOSE SCIENCE AND TECHNOLOGY BUILDING

The Multipurpose Science and Technology Building (MSTB) was evaluated for the addition of a fuel cell system. The average electricity demand of MSTB is 83.5 kW, the average heating demand is 27.1 kW and the average cooling demand is 17.6 kW (5 refrigeration tons). In order to get a baseline for comparison, the competing scenario was run which simulated the current configuration of utilities at MSTB. The equipment portfolio of the competing system consists of electricity imports from the grid, a natural gas boiler for heating, and an electric chiller for cooling. The LCOE of the competing scenario at MSTB is $133.46/MWh. A breakdown of LCOE by component is shown in Figure 5.

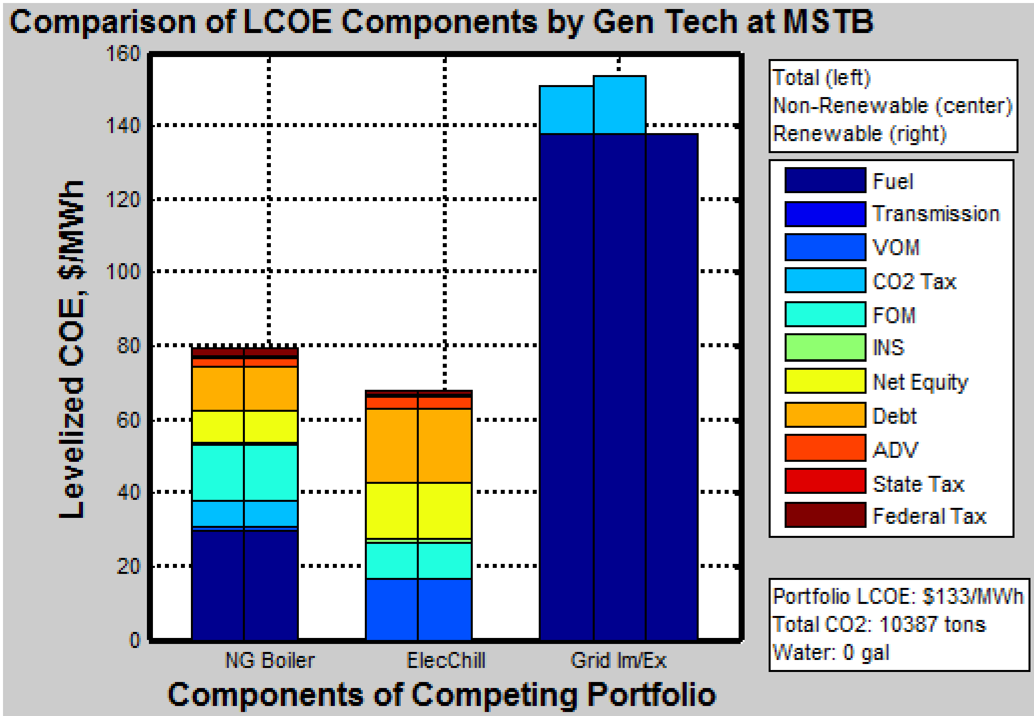

Figure 5: MSTB Competing Scenario

The average power demand of the building is only 83.5 kW, so each of FuelCell Energy's molten carbonate fuel cells are oversized for this application and would export a majority of the electricity produced. For the MSTB, a basic portfolio consisting of a 300 kW fuel cell and a 40 refrigeration ton absorption chiller does not meet any of the building's heating demand but satisfies 99% of its chilling demand while exporting 69% of the electricity generated. Figure 6 shows a breakdown of the LCOEs for each component.

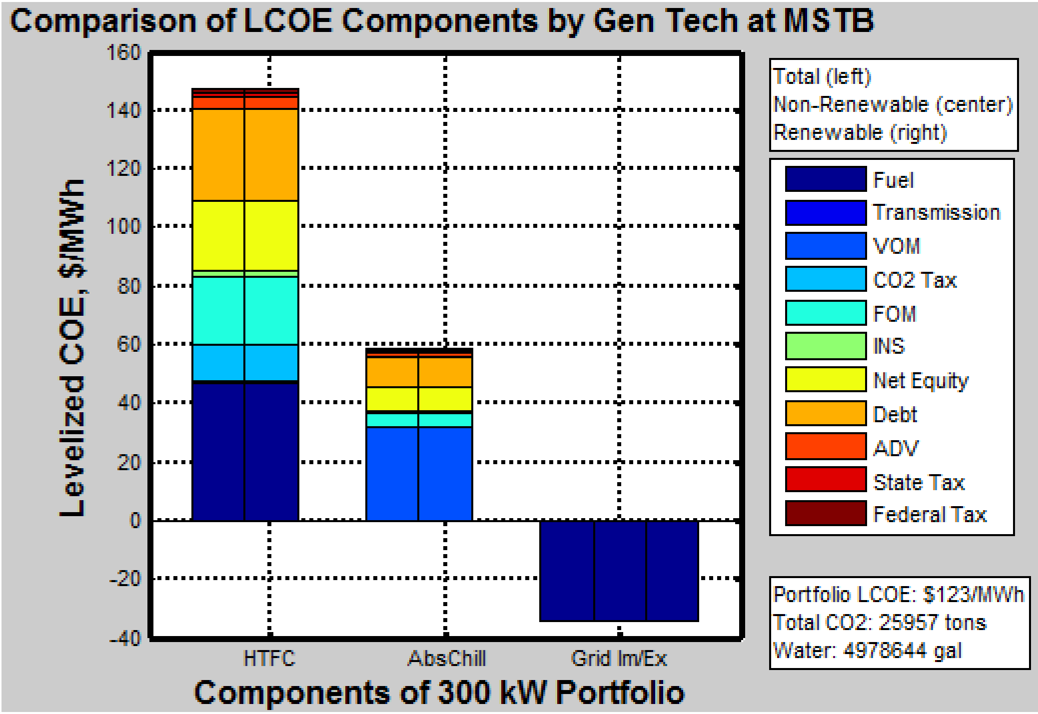

Figure 6: MSTB 300 kW Portfolio

If a 30 kW heat recovery unit (HRU) is included in the equipment portfolio, the LCOE of the system is reduced slightly as more useful energy is produced from the system, but with the dynamic heating load profile at MSTB, the HRU only meets 18.5% of the heating load. Figure 7 shows the breakdown of LCOEs for this portfolio.

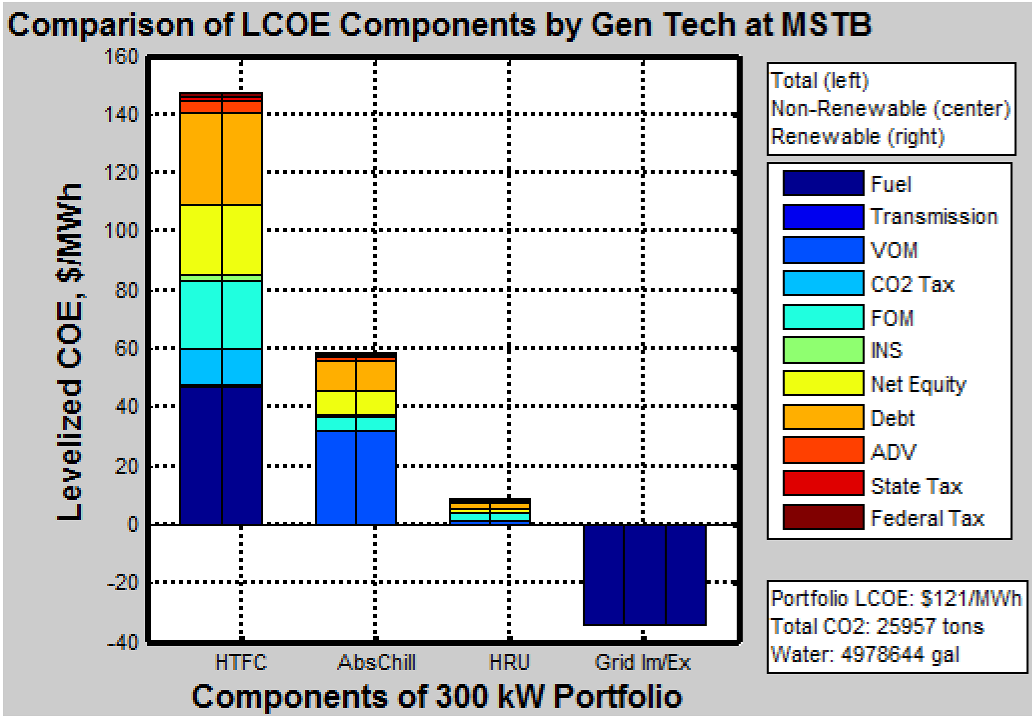

Figure 7: MSTB 300 kW Portfolio with HRU

The Heat Recovery Unit (HRU) has an extremely low LCOE because it constantly recovers heat from the fuel cell exhaust throughout its years of operation and requires comparatively little installation and operating costs. Since the HRU decreases the LCOE for this case, it is left in the equipment portfolio and supplemented with a natural gas boiler to meet the building heating demand as shown in the results of Figure 8.

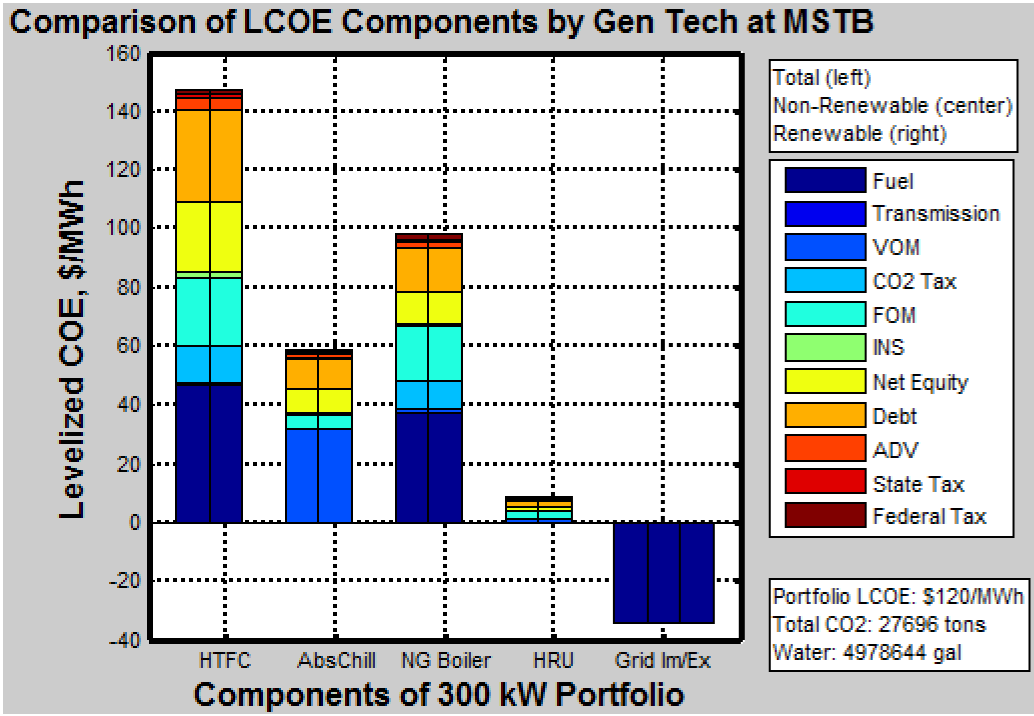

Figure 8: MSTB 300 kW Portfolio with HRU and NG Boiler

This scenario represents the least amount of distributed generation equipment with the smallest capacity required to meet all of the loads of the MSTB (except 1% of the cooling). The LCOE of this scenario is $14/MWh (10%) less than the competing scenario.

Next the 1.4 MW portfolios are evaluated for installation at MSTB. The smallest portfolio that has the potential to meet all of the heating, cooling, and power demands of the building is the simple fuel cell, absorption chiller, and heat recovery unit setup. The LCOE of this scenario is $111.3/MWh, but only 75% of the heating demands are met. Cooling demands are met 99.5% of the time, so an electric chiller is not required. When a natural gas boiler is added to the portfolio, the LCOE is $111.4/MWh. In this case, the HRU provides 3/4 of the heating while the natural gas boiler is designed to meet 1/4 of the heating demand. Figure 9 shows the

LCOEs for each component in this scenario. The installation of this equipment at MSTB would save the owner $22.1/MWh (17%) on energy costs over the next 20 years.

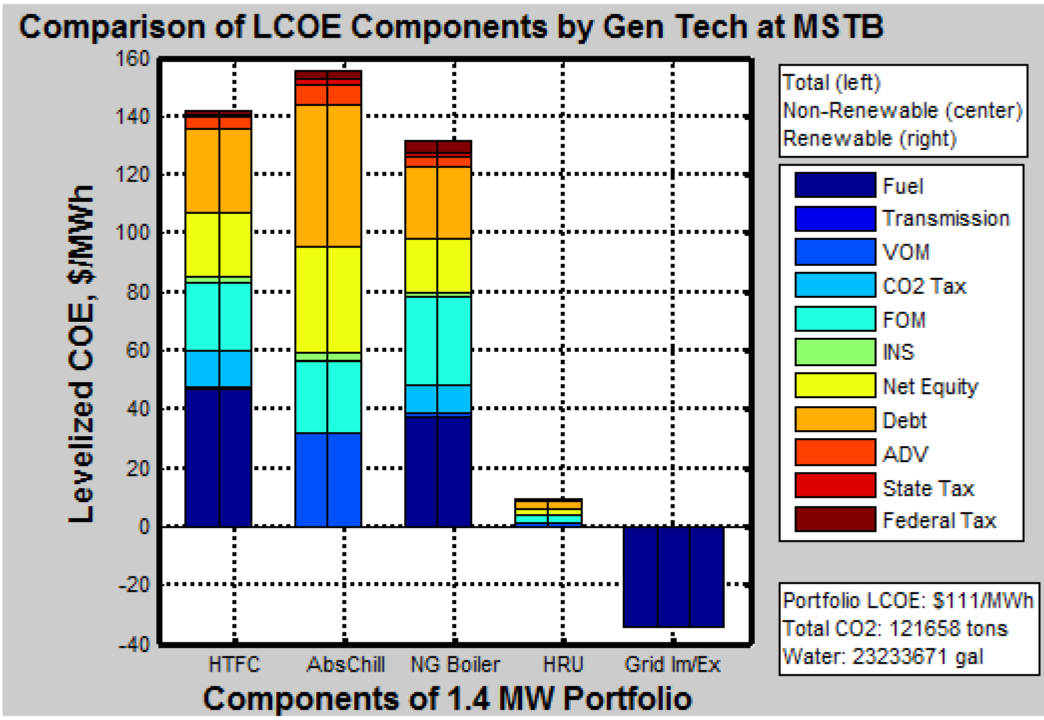

Figure 9: MSTB 1.4 MW Portfolio with HRU and NG Boiler

Over %91 of the electricity produced by the fuel cell is exported back to the grid, and in the default scenario the owner receives $30/MWh plus inflation for this exported electricity. The installation cost for the 300 kW fuel cell is assumed to be $3600/kW in the g-matrix. Economy of scale reduces this cost for the 1.4 MW fuel cell to $3300/kW. Since this installation price per kilowatt is lower, and more revenue is generated from exports, the 1.4 MW system more economically viable than the 300 kW system. Economies of scale further reduce the installation cost of the fuel cell to $3000/kW for a 2.8 MW unit. In this case, the fuel cell produces enough exhaust to run a 400 refrigeration tons absorption chiller so there is extra cooling capacity available. Also, the HRU is large enough to accommodate all of the

MSTB heating loads, so that no natural gas boiler is required. Revenue from exports, reduced installation rate and a smaller equipment portfolio each contribute to the very low LCOE for this portfolio as shown in Figure 10. This scenario is $27.7/MWh (21%) less than the competing system at MSTB.

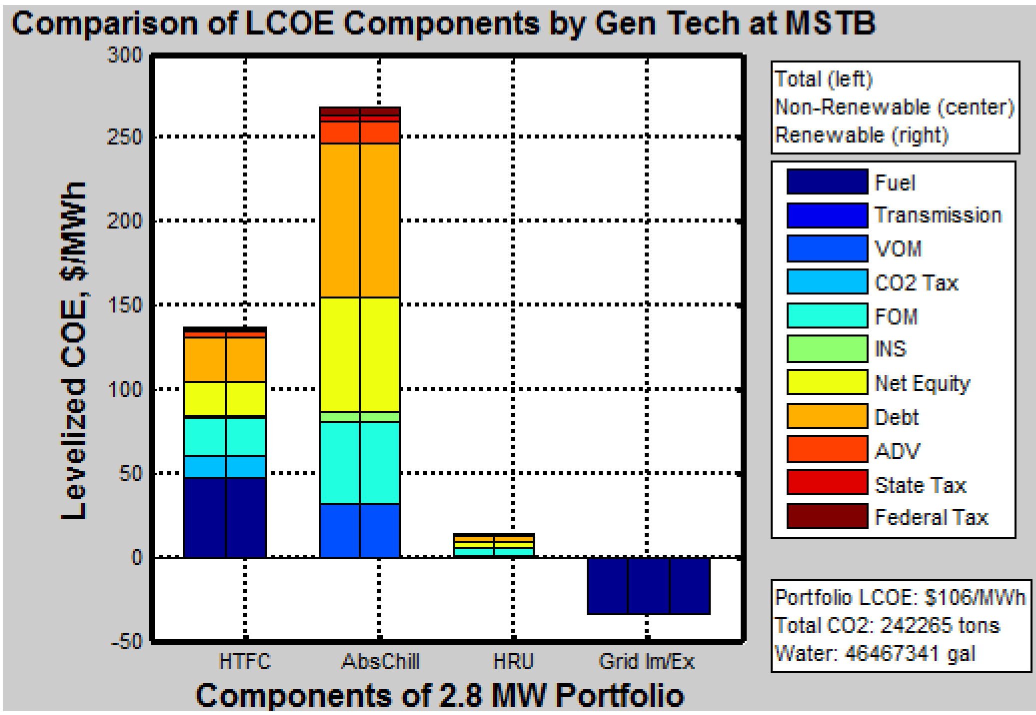

Figure 10: MSTB 2.8 MW Portfolio with HRU

This equipment portfolio offers no backup source of cooling or heating for the absorption chiller and natural gas boiler. In each of the preceding scenarios, which include a natural gas boiler, the boiler is sized to meet the heating load that is not met by the heat recovery unit. If the owner wished to add redundancy to the system shown in Figure 10, they could add an electric chiller and a natural gas boiler sized to meet 100% of the required heating and cooling loads. Adding this redundant equipment hardly affects the LCOE as the overall cost is allocated on a per-megawatt basis, and the system produces a large amount of energy. A 2.8

MW fuel cell with a 400 ton absorption chiller, a heat recovery unit, and a full backup natural gas boiler and electric chiller would have an LCOE of $106.87.

Each of the preceding scenarios assumes the owner received $30/kWh for exported electricity. While this rate is conservatively four times less than the assumed rate for imported electricity, in some situations the electric utility may deny the owner the ability to collect any money for exported electricity. This would drastically reduce the economic viability of each of the three portfolios as shown in Figures 11, 12, and 13.

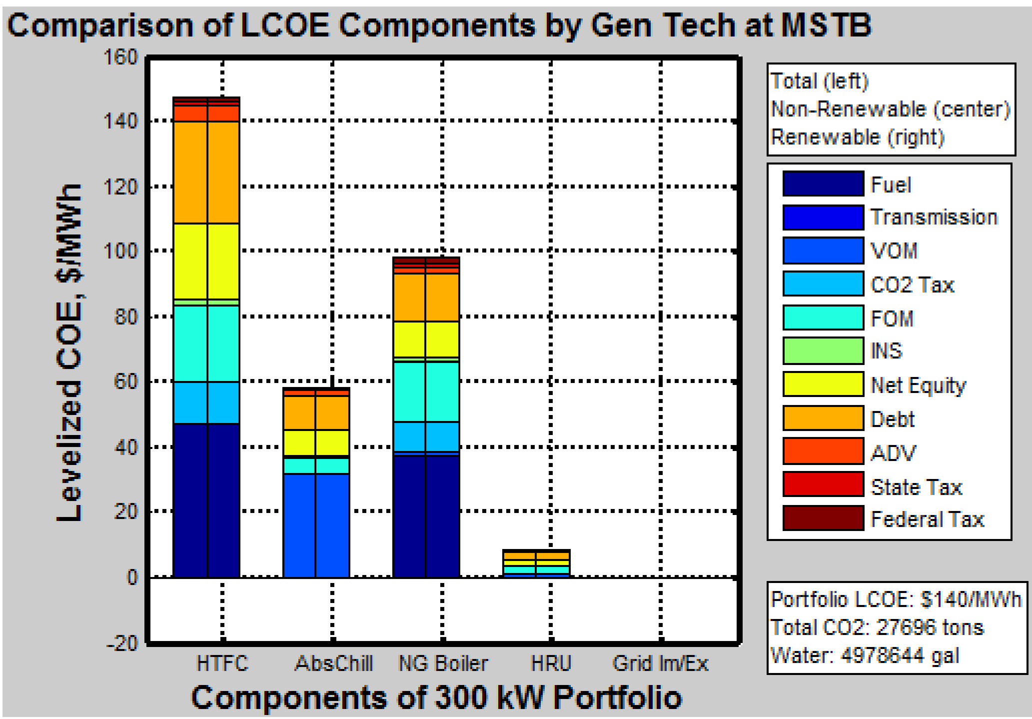

Figure 11: MSTB 300 kW Portfolio with Zero Return on Exports

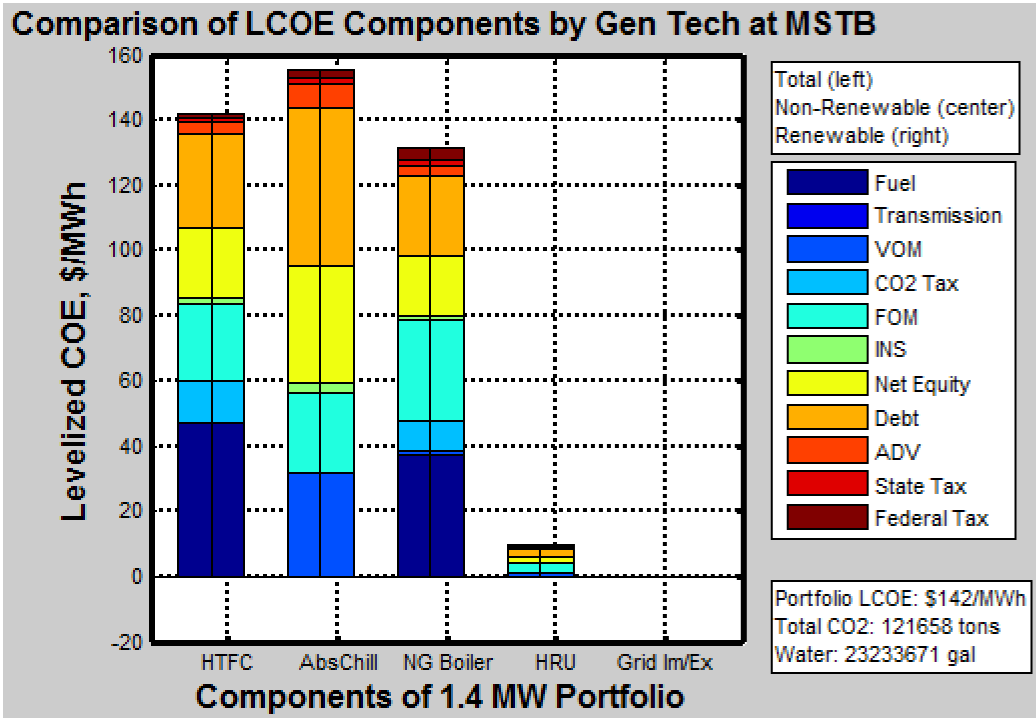

Figure 12: MSTB 1.4 MW Portfolio with Zero Return on Exports

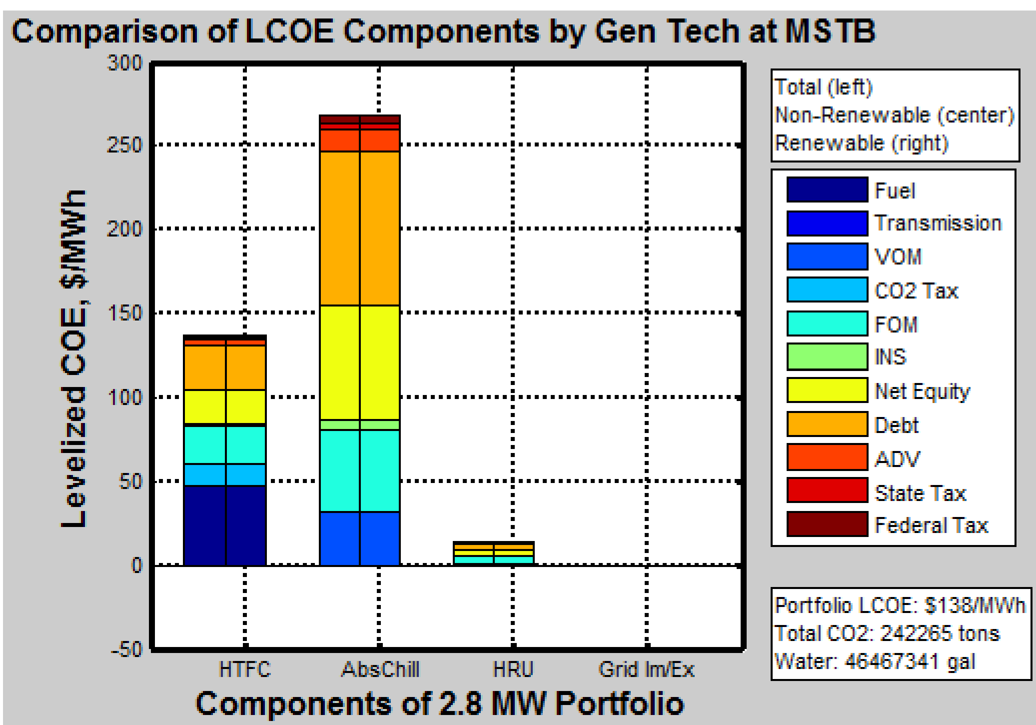

Figure 13: MSTB 2.8 MW Portfolio with Zero Return on Exports

None of the HTFC/AC portfolios at MSTB are economically competitive with using grid electricity, a natural gas boiler and an electric chiller when the owner is not being reimbursed for electricity exports from the fuel cell. The 300 kW fuel cell portfolio was 10% more economical than the competing system when exported electricity had a $30/MWh return rate, but is 6% more expensive than the competing scenario when exports are not reimbursed. Similarly, the 1.4 MW portfolio goes from being 17% more economical to being 8% more expensive, and the 2.8 MW portfolio goes from being 21% more economical to being 4% more expensive. The 2.8 MW portfolio is slightly less expensive than the 1.4 MW portfolio when exports are not reimbursed as the savings from exclusion of a natural gas boiler are more prominent.

These results beg the question, what is the minimum payback on exported electricity required for an HTFC/AC system at MSTB to break even with the traditional power, heating, and cooling portfolio of the competing system? In order to answer this question, the exported electricity payback rate was varied for each fuel cell portfolio until the LCOE of the HTFC/AC system matched the LCOE of the competing portfolio. Figure 14 shows the LCOE breakdown for a 300 kW fuel cell portfolio. Similarly, the LCOE of this equipment portfolio closely matches the competing system when the owner is receiving $10/MWh on exported electricity. The 1.4 MW and 2.8 MW portfolios require at least $8/MWh and $4/MWh return on exported electricity in order to be competitive.

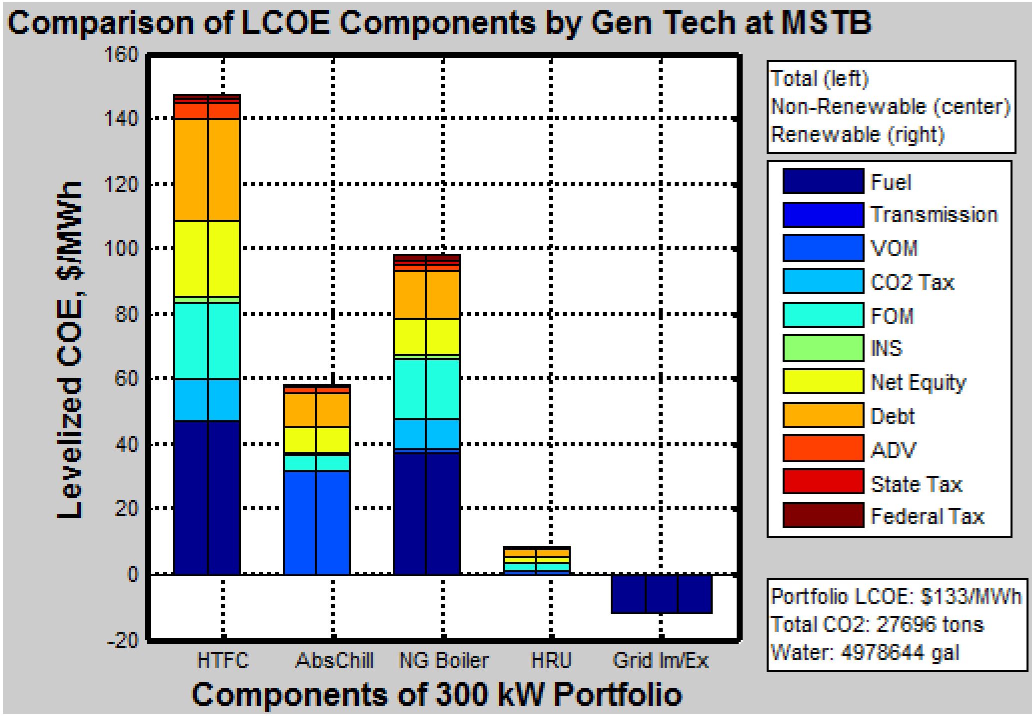

Figure 14: MSTB 300kW System with $10/MWh Return on Exports

Due to the agreement between the University of California, Irvine and their electricity utility, the University would not receive reimbursement for electricity exported back to the grid from a distributed generation fuel cell at MSTB. However, the unique regulatory environment in California could improve the chances of an HTFC/AC system being cost competitive at MSTB. California Senate Bill 32 sets the groundwork for the state's plan to cap greenhouse gas emissions. The bill is implemented under regulations set forth by the California Air Resources Board. In Article 5 of the Air Resources Board "Final Regulation Order on California Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms," section 95852.2, fuel cells are explicitly exempt from CO_2 taxes. The HTFC/AC system shown in Figure 14 simulated at MSTB with zero CO_2 taxes has a portfolio LCOE of $108.5/MWh, 19% lower than the competing scenario.

In conclusion, a 2.8 MW fuel cell with a 400 ton absorption chiller, an HRU, and an optional backup electric chiller and natural gas boiler could be installed at a building with a similar load profile to the Multipurpose Science and Technology Building and be economically competitive with the existing infrastructure if a reasonable rate of return is achieved for electricity exports. The high revenue on electricity exports and lower installation rates associated with such a large unit will make this distributed generation option economically feasible. However, the logistics of constructing such a large system next to a relatively small building in a populated area could pose some challenges to the adoption of this technology by the distributed generation market. Also, if the owner is not receiving returns on exported electricity, the megawatt class fuel cells become economically uncompetitive. Since distributed generation owners are typically in the business of offsetting their own loads rather than exporting electricity, the smaller 300 kW HTFC/AC system is advisable as it is the smallest unit capable of meeting all of the loads at MSTB. The actual situation at MSTB is that the owner would receive no reimbursements for exported electricity, but would also not be taxed on the CO_2 produced by the fuel cell. In this case, the 300 kW HTFC/AC system with a natural gas boiler and heat recovery unit would be economically advisable.

4.2.2 LONG BEACH VETERANS AFFAIRS HOSPITAL

The Long Beach Veterans Affairs Hospital (LBVA) has an average power demand of 3.51 MW, an average cooling demand of 1924 kW (547 refrigeration tons), and an average heating demand of 1,938 kW. The competing scenario at LBVA of a natural gas boiler, an electric chiller, and electricity from the grid has an LCOE of $102.9268/MWh and produces 514,556 short tons of CO_2. The 300 kW system could be installed at LBVA to supplement the existing infrastructure and reduce overall CO_2 emissions by 6% at an LCOE of $101.09. The component LCOEs for this system are shown in Figure 15.

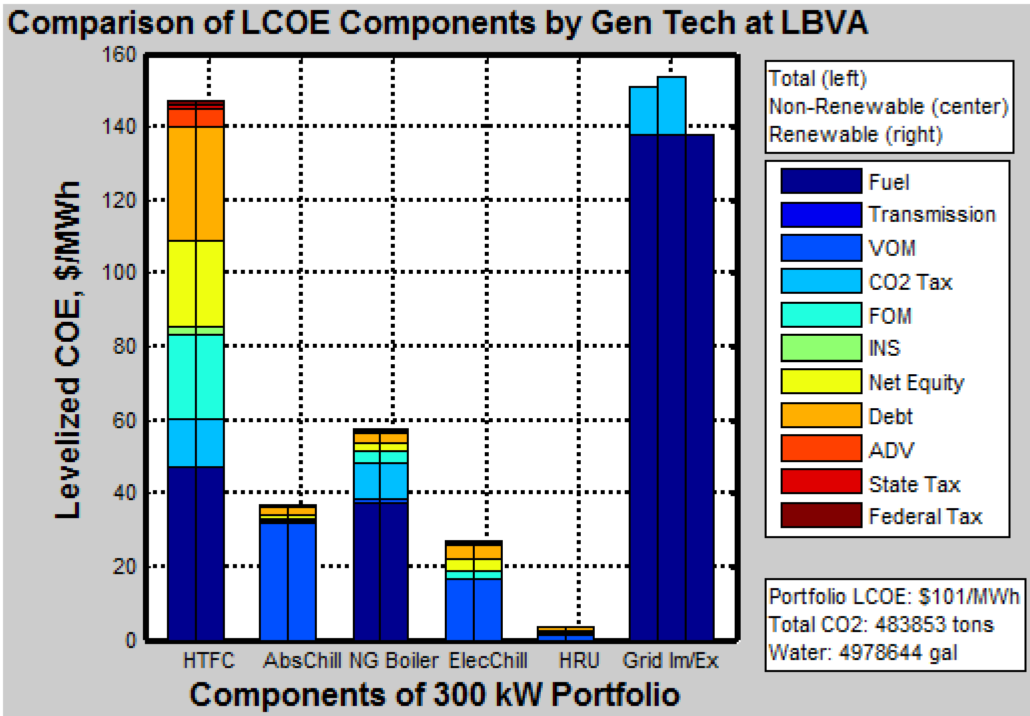

Figure 15: LBVA 300 kW System

A 1.4 MW fuel cell is capable of providing 40% of the building's electricity demand on average. It can also drive a 200 ton absorption chiller, which is capable of satisfying 94% of the building's cooling demand. The portfolio LCOE for a 1.4 MW HTFC/AC distributed generation system which satisfies all of the cooling and heating loads of the hospital is shown in Figure 16. The LCOE of such a system is economically competitive with the existing infrastructure.

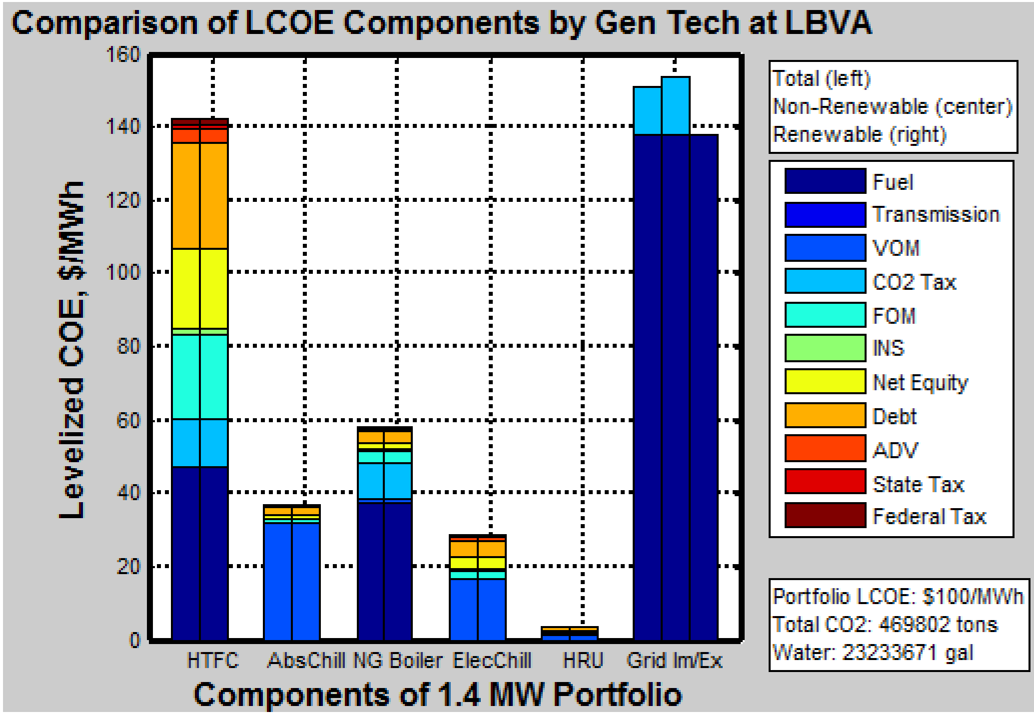

Figure 16: LBVA 1.4 MW System

A 2.8 MW fuel cell is capable of providing 80% of the building's electricity demand on average. It also can drive a 400 ton absorption chiller which is capable of satisfying all of the building's average cooling demand, but spikes in cooling demand require an electric chiller. The portfolio LCOE for a 2.4 MW HTFC/AC distributed generation system which satisfies all of the cooling and heating loads of the hospital is shown in Figure 16. The LCOE of such a system is similar to the LCOE of a 1.4 MW system, and is competitive with the existing infrastructure. There is a slight decrease in the LCOE of the 2.8 MW system compared to the 1.4 MW system because the increased revenue from exports and decreased installation cost on a per-megawatt basis.

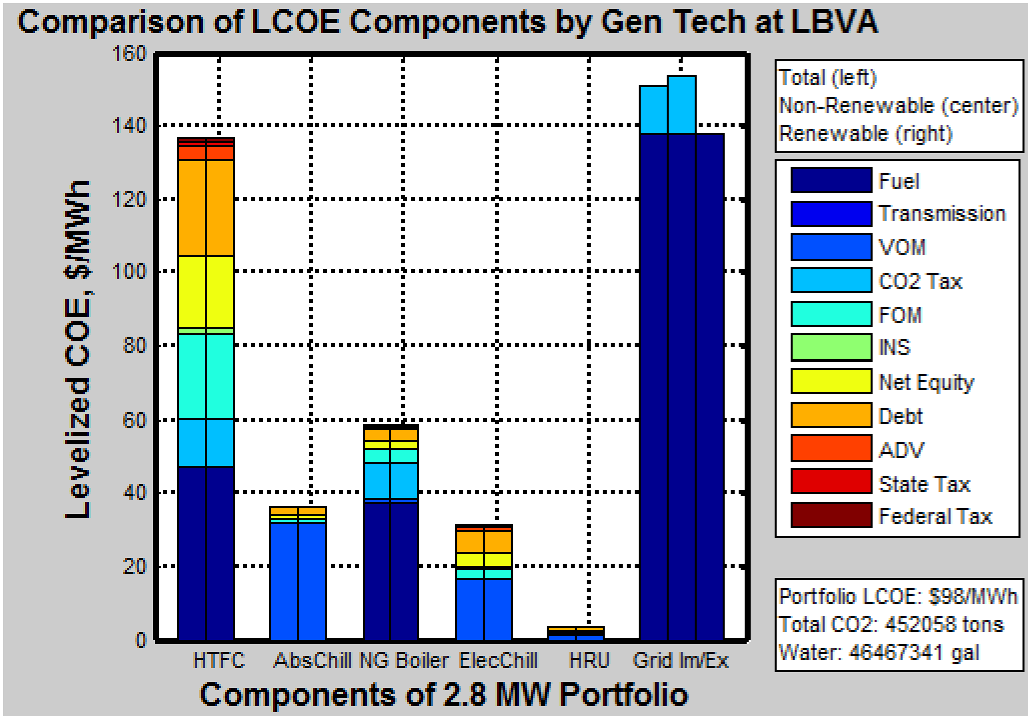

Figure 17: LBVA 2.8 MW Portfolio

The 2.8 MW portfolio saves the investor 5.2% on energy charges when levelized over the 20 year life of the project. If California Senate Bill AB-32 is assumed to be in effect, and the CO_2 emissions from the fuel cell are not taxed, the portfolio would be even more economically advisable with an LCOE of $93.1/MWh, which is 9.5% less than competing scenario.

The cooling load of the LBVA is 547 refrigeration tons on average, so the 400 ton absorption chiller is usually fully loaded by the hospital. However, the standard deviation of the cooling profile at LBVA is 595 tons, so the load is very dynamic, frequently rising above the average demand. The electric chiller is sized to meet all of the excess cooling demand not met by the absorption chiller. Electricity used to run the electric chiller along with the associated CO_2 emissions created by the grid increase the overall LCOE of the portfolio. The addition of a thermal energy storage tank could curtail the cooling demand of the electric chiller by storing excess cooling produced by the absorption chiller during times of low cooling demand, and later dispatching that cooling to meet loads when then are above the capacity of the absorption chiller. An economic model is run using the 2.8 MW system to see what impact the addition of a thermal energy storage tank has on the economics of the HTFC/AC application. For this example, the tank is assumed to be able to deliver cooling at a rate of 300 refrigeration tons to the hospital. This is based on a rough estimate 750 gallons per minute of chilled water flowing through an 8” steel pipe between the tank and the hospital. The water is assumed to increase in temperature by 10^oF across the air conditioning coils. The thermal energy storage tank capacity is assumed to be 500 ton-hrs. This is based on the amount of excess cooling typically provided by the absorption chiller when cooling loads of the building are low. The LCOE of this portfolio is $98.05/MWh, which is only slightly higher than the 2.8 MW portfolio without a thermal energy storage tank. While the tank is expensive to install, it saves roughly 100 short tons of CO_2 emissions by reducing the utilization of the electric chiller

In conclusion, while the addition of any size HTFC/AC system reduces energy costs for the LBVA, the 2.8 MW fuel cell coupled with a 400 refrigeration ton absorption chiller, heat recovery unit, natural gas boiler, and electric chiller portfolio is the most cost effective solution. Even if the owner does not receive incentives for exported electricity, and is taxed $30/MWh on CO_2 emissions from the fuel cell, the HTFC/AC system is 5.2% more economical than the existing infrastructure.

4.2.3 SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT BUILDING

The South Coast Air Quality Management District Building (SCAQMD) has an average power demand of 253 kW, an average cooling demand of 176 kW (50 refrigeration tons), and an average heating demand of 294 kW. The competing scenario at SCAQMD of a natural gas boiler, an electric chiller, and electricity from the grid has a very low LCOE of $85.52/MWh and produces 51,697 short tons of CO_2. A 300 kW fuel cell system could be installed at SCAQMD and would only require grid support 30% of the time when electric demands are high. The 40 refrigeration ton absorption chiller coupled to the fuel cell is capable of handling 94.8% of the total cooling load and the heat recovery unit can handle 6.2% of the heating load. With the addition of a natural gas boiler and an electric chiller, the system is capable of handling all of the cooling and heating loads of the building at an LCOE of $85.3/MWh as shown in Figure 15.

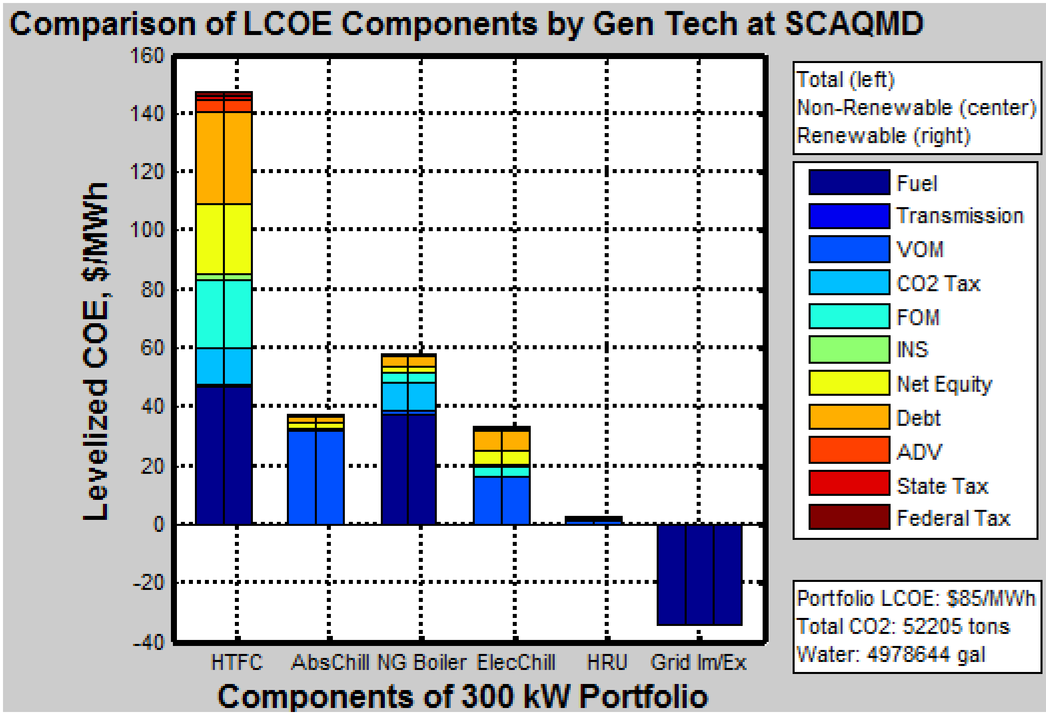

Figure 18: SCAQMD 300 kW System

If CO_2 taxes are not applied to the fuel cell, the LCOE of this system drops to $81.3/MWh which is almost 5% more economical than the competing system. If the owner is not being reimbursed for exported electricity, the LCOE is $86.9/MWh.

A 1.4 MW fuel cell is capable of providing all of the building's electricity. It also can drive a 200 ton absorption chiller, which is capable of satisfying 99% of the building's cooling demand, so the addition of an electric chiller would be optional. The portfolio LCOE for 1.4 MW and 2.8 MW HTFC/AC distributed generation systems deployed at SCAQMD are shown in Figure 19 and Figure 20.

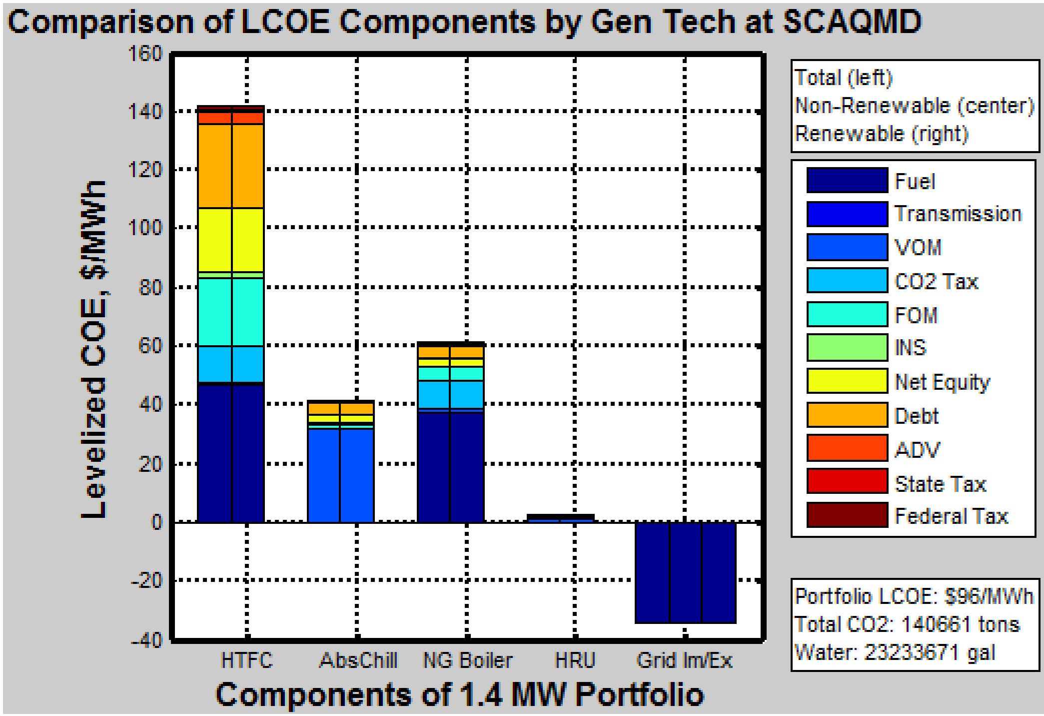

Figure 19: SCAQMD 1.4 MW Portfolio

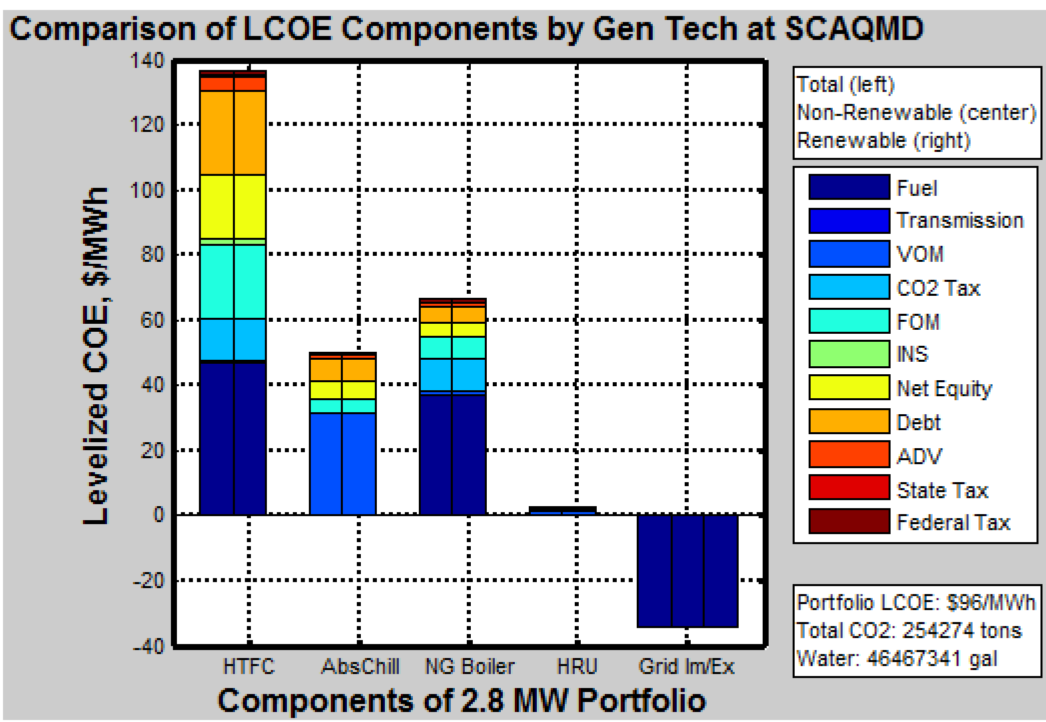

Figure 20: SCAQMD 2.8 MW Portfolio

The competing scenario at SCAQMD has a very low LCOE because the load profile of the building is relatively flat, thus making it very hard for HTFC/AC systems to compete. See 4.2.4 for an in-depth analysis of the implications of building load profiles.

If CO_2 taxes were not applied to the 1.4 and 2.8 MW portfolios above, their LCOEs would drop to $82.8/MWh and $82.7/MWh respectively.

In conclusion, when CO_2 taxes are applicable to the fuel cell, the most economically competitive equipment portfolio at the SCAQMD is the 300 kW fuel cell with a 40 ton absorption chiller, a natural gas boiler, an electric chiller, and a heat recovery unit. The larger units can only compete with the relatively low LCOE of the competing scenario if there are no CO_2 taxes applied to the fuel cell.

4.2.4 COMPARISON OF BUILDING TYPES

The three building load profiles analyzed above represent potential real world applications of High Temperature Fuel Cell and Absorption Chiller (HTFC/AC) technology. Each of the load profiles have unique characteristics which influence the levelized cost of whichever system is installed. These unique characteristics make it difficult to draw overarching conclusion about the behaviors and trends of fuel cell system LCOEs because there are so many variables to account for. In order to simplify the task of characterizing LCOE trends, three dummy load profiles were created which simulate the perfect building for each size equipment portfolio. The Test 300 data set represents a building which draws a flat 300 kW electric load, 40 refrigeration ton cooling load, and 30 kW heating load which can be precisely served by the 300 kW fuel cell, 40 ton absorption chiller, and heat recovery unit portfolio. Similarly, the Test

1400 data set represents a building tailored to the power, cooling, and heating loads of the 1.4 MW fuel cell, 200 ton absorption chiller, and 140 kW heat recovery unit portfolio. Test 2800 is tailored for the 2.8 MW fuel cell, 400 ton absorption chiller, and 280 kW heat recovery unit portfolio. The competing scenario was run for each tailored building load profile in order to see what the LCOE would be for a typical grid-reliant setup. Then, each of the fuel cell portfolios was run using each of the tailored load sets. The portfolio was adjusted to ensure all of the loads of the building were being met. An electric chiller and a natural gas boiler were added to the 300 kW portfolio when analyzing the 1.4 and 2.8 MW buildings, and to the 1.4 MW portfolio when analyzing the 2.8 MW building. The result of this exercise is shown below in Figure 21 and Table 4.

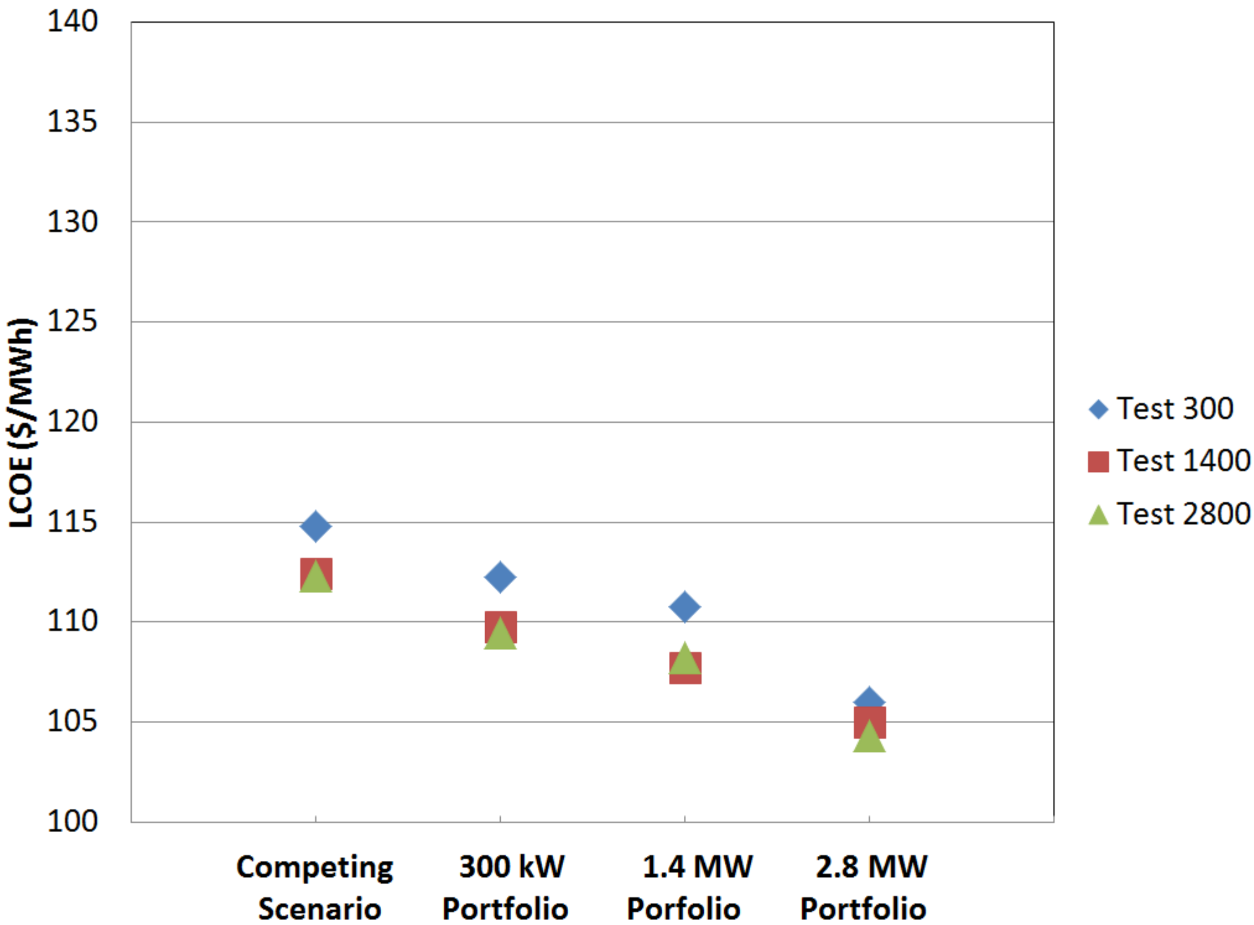

Figure 21: Tailored Building Results

Table 4: Tailored Building Run Data

Portfolio	Building	LCOE ($/MWh)	CO_2 (tons)	H2O (gal)	Imported Elec (MWh)
0 0 0 0 0 0 1 1 0 0 1	Test 300	114.8	32107.5	0.0	53826.4
1 0 0 1 0 0 0 0 0 1 1	Test 300	112.3	25770.6	4978643.7	-4770.4
0 1 0 0 1 0 0 0 0 1 1	Test 300	110.8	120262.7	23233670.6	-171794.4
0 0 1 0 0 1 0 0 0 1 1	Test 300	106.0	240525.5	46467341.2	-384370.4
0 0 0 0 0 0 1 1 0 0 1	Test 1400	112.4	151068.9	0.0	253363.9
1 0 0 1 0 0 1 1 0 1 1	Test 1400	109.7	128645.3	4978643.7	167955.9
0 1 0 0 1 0 0 0 0 1 1	Test 1400	107.7	120262.7	23233670.6	-24435.9
0 0 1 0 0 1 0 0 0 1 1	Test 1400	105.0	240525.5	46467341.2	-237011.9
0 0 0 0 0 0 1 1 0 0 1	Test 2800	112.3	302137.8	0.0	506727.9
1 0 0 1 0 0 1 1 0 1 1	Test 2800	109.5	263844.2	4978643.7	388707.9
0 1 0 0 1 0 1 1 0 1 1	Test 2800	108.2	239808.5	23233670.6	195126.0
0 0 1 0 0 1 0 0 0 1 1	Test 2800	104.3	240525.5	46467341.2	-48871.9

The first obvious conclusion is that HTFC/AC systems make economic sense when they are deployed at buildings that can accept all of their electricity, cooling, and heating products without relying on the grid for supplemental electricity. Also, bigger fuel cell capacities lead to smaller LCOEs when the owner is being reimbursed at a price of only $30/MWh for exports back to the grid. In this case, the owner is being reimbursed $30/MWh for exports back to the grid. However, they are not receiving the entire $30/MWh back for exported electricity as increased production means increased CO_2 taxes and other maintenance and operation costs.

In the base case, the CO_2 tax rate is assumed to be \$20/ton of CO_2. Since the fuel cells have a CO_2 emissions factor of 0.49 tons per MWh, there is a tax charge of \$9.8/MWh of generation. Therefore, the owner is realizing a return of \$20.2/MWh on exported electricity. If the CO_2 tax rate were increased to \$61.2/ton the export return of \$30/MWh would be cancelled out and there would be no incentive at all to export.

If the same model runs are performed assuming the owner is not reimbursed for exporting electricity to the grid, LCOE trends change dramatically as shown in Figure 22.

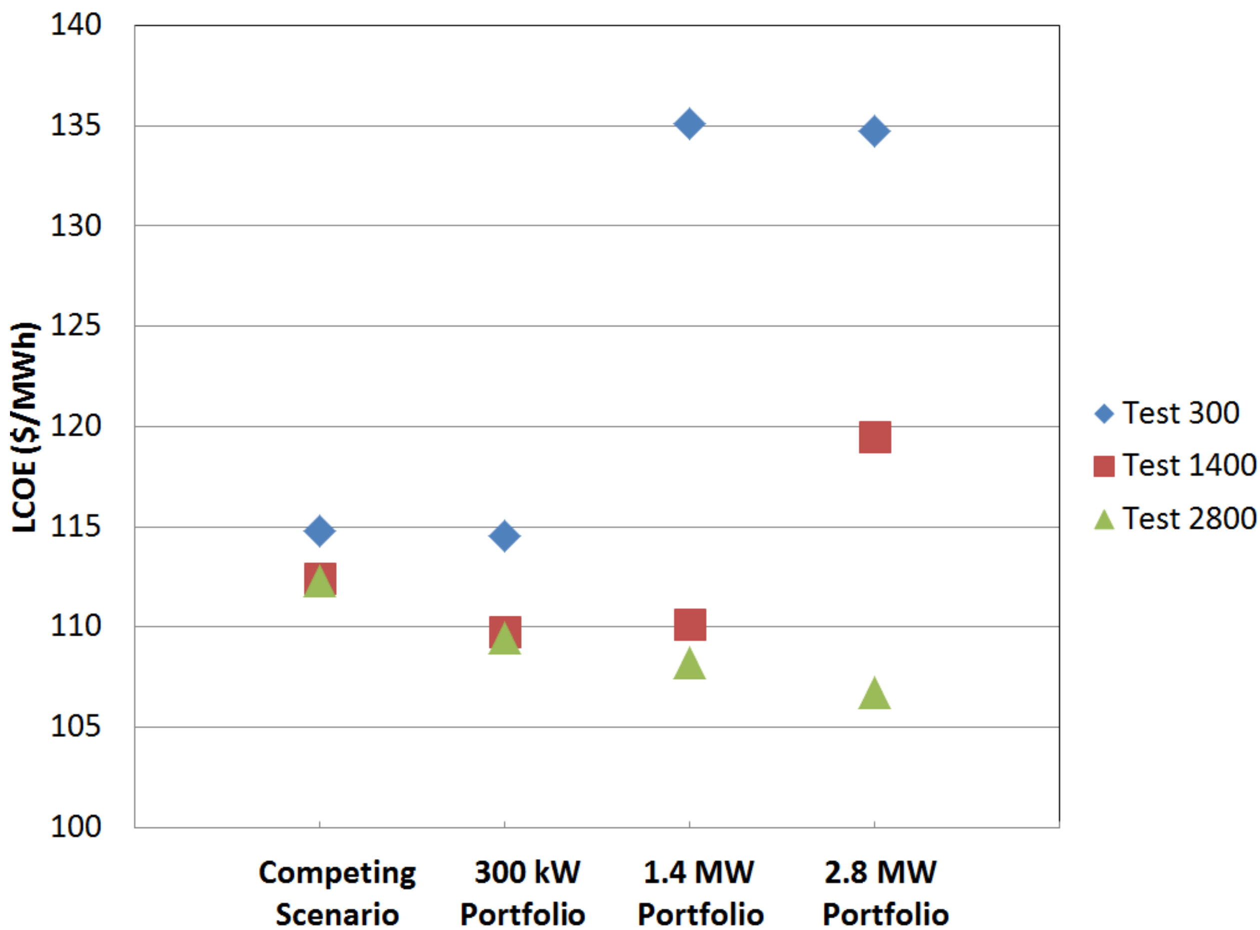

Figure 22: Tailored Building Results with Zero Return on Exports

There is a heavy penalty for installing fuel cells with extra capacity when there are no export reimbursements. These results also suggest that installing an HTFC/AC portfolio that is smaller than the building demand at all times leads to the lowest LCOE, which makes sense since the equipment is utilized to its maximum potential to meet the building demands for cooling, heating, and power. The Test 300 building benefits slightly from the installation of a 300 kW fuel cell, but the 1.4 MW and 2.8 MW fuel cells cause an increase in LCOE of 17%. The Test 1400 building also benefits from the installation of a 300 kW or a 1.4 MW fuel cell, but a 2.8 MW fuel cell would increase the LCOE by nearly 6%. The large Test 2800 building sees the biggest benefit from installing a HTFC/AC system, with the savings increasing with fuel cell size up to 7%. These findings agree with predictions, but do not completely agree with the results of the real-world building analysis done in prior sections of this thesis, specifically, the results of the SCAQMD analysis. To determine why the megawatt-class HTFC/AC portfolios at SCAQMD do not follow the trends outlined above, the load characteristics of each of the buildings must be compared.

As Table 6 shows, the biggest savings occur at the buildings with the highest competing scenario LCOEs. Since the SCAQMD already has such a low LCOE, it will be difficult for any HTFC/AC system to make economic sense. As was shown in Section 4.2.3, the 300 kW portfolio is the most economic HTFC/AC solution at just 0.26% lower than the competing scenario.

Table 5: Best Case HTFC/AC Scenarios

		HTFC/AC System LCOE	
Building	Competing Scenario LCOE ($/MWh)	Savings with Exports $30/MWh	Savings with Exports $0/MWh
MSTB (300 kW)	133.4	10.5%	-4.6%
LBVA (2.8 MW)	102.9	5.2%	5.2%
SCAQMD (300 kW)	85.5	0.26%	-1.6%
Test 300	114.76	7.6%	7.6%
Test 1400	112.4	6.6%	6.6%
Test 2800	112.3	7.15%	7.15%

Table 6 summarizes the load characteristics of each of the three buildings analyzed in Sections 4.2.1, 4.2.2, and 4.2.3 of this thesis. The heating or cooling thermal-to-electrical load ratio (T/E) is the ratio of the average heating or cooling demand to the average electricity demand of the building and is an indication of how much of a specific thermal product is demanded relative to electric power. The relative standard deviation is the standard deviation of the load profile divided by the average demand; it gives an indication of the variability of the load profile.

Table 6: Building Load Statistics

	Power		**Cooling**			**Heating**		
Building Name	Avg. Demand (kW)	Relative Standard Deviation (%)	Avg. Demand (tons)	T/E Ratio	Relative Standard Deviation (%)	Avg. Demand (kW)	T/E Ratio	Relative Standard Deviation (%)
MSTB	83.5	29.7	5	.210	227.6	27.1	.325	253.6
SCAQMD	252.9	35.0	49.9	.694	135.2	293.5	1.16	103.5
LBVA	3510	16.2	547.1	.548	108.8	1937.7	.552	96.1

The heating and cooling loads of the SCAQMD are so small and variable that the returns gained on exported electricity are offset by the extra cost of installing and maintaining a 200 or 400 ton absorption chiller and associated heat recovery unit.

In conclusion, the optimal HTFC/AC equipment portfolio and building load profile combination will leverage the cooling and heating made available by recovery of energy from the exhaust gas of the fuel cell. If the HTFC/AC system is properly sized for the building (i.e., its thermal and electrical products are being utilized to their maximum potential) and is installed in California under AB-32's CO_2 tax exemption for fuel cells, it will be highly competitive with the existing infrastructure regardless of the return rate on exported electricity. If CO_2 taxes do apply to the fuel cell, then a closer look at the electricity exporting agreement between the owner and their electric utility will reveal whether the HTFC/AC system is economically advisable.

4.3 IMPACT OF DEPLOYMENT FACTORS

The impact of CO_2 tax rate and exported electricity return rate were examined in Section 4.2 of this thesis as they directly applied to the real-world application of HTFC/AC systems at the buildings analyzed. Other important factors that were not directly pertinent to the scenarios already assessed, but which could have a large impact on HTFC/AC portfolio LCOEs include equipment capacity factors, ownership type, and fuel cell costs. Each of these items are addressed in this Section to provide more insight to the economic behavior of HTFC/AC systems.

4.3.1 CAPACITY FACTOR SENSITIVITY TESTING

The annual capacity factor for any piece of equipment is the ratio of actual output in a year to potential output in a year if the equipment operated continuously at its full rated capacity. When a fuel cell is sized to meet the minimum electrical load of a building, it is being used as a base load source of electricity with a high capacity factor, which results in the lowest portfolio LCOE if everything else is held constant. In order to further investigate the effect of capacity factor on LCOE, sensitivity analysis was performed using Scenario Type 0, which calls upon the default equipment parameters held in the G-Matrix instead of calculating actual engineering values. The annual capacity factor for each piece of equipment was varied from 0.2 to 1 to examine the relative impact on LCOE.

As expected, the results in Figure 23 show a dramatic decrease in the fuel cell's LCOE when capacity factor is increased. It is also clear that the LCOE of the TES strongly correlates with capacity factor. The magnitude of capital costs associated with fuel cells and the TES is much larger than for the other pieces of equipment. The LCOE is strongly affected at low capacity factors because the amount of output over which to allocate those higher fixed capital costs is so much smaller than at higher capacity factors. Figure 24 shows the results of the less significant pieces of equipment, and it is apparent that the same effect is prevalent in each type of equipment.

In order to maximize the economic viability of a HTFC/AC system, each piece of equipment should be sized to operate at or near full capacity a majority of the time. The sizing of the fuel cell is the most important factor, as the magnitude of capital cost for a fuel cell is much larger than any other component, and its effect on overall portfolio LCOE is the greatest.

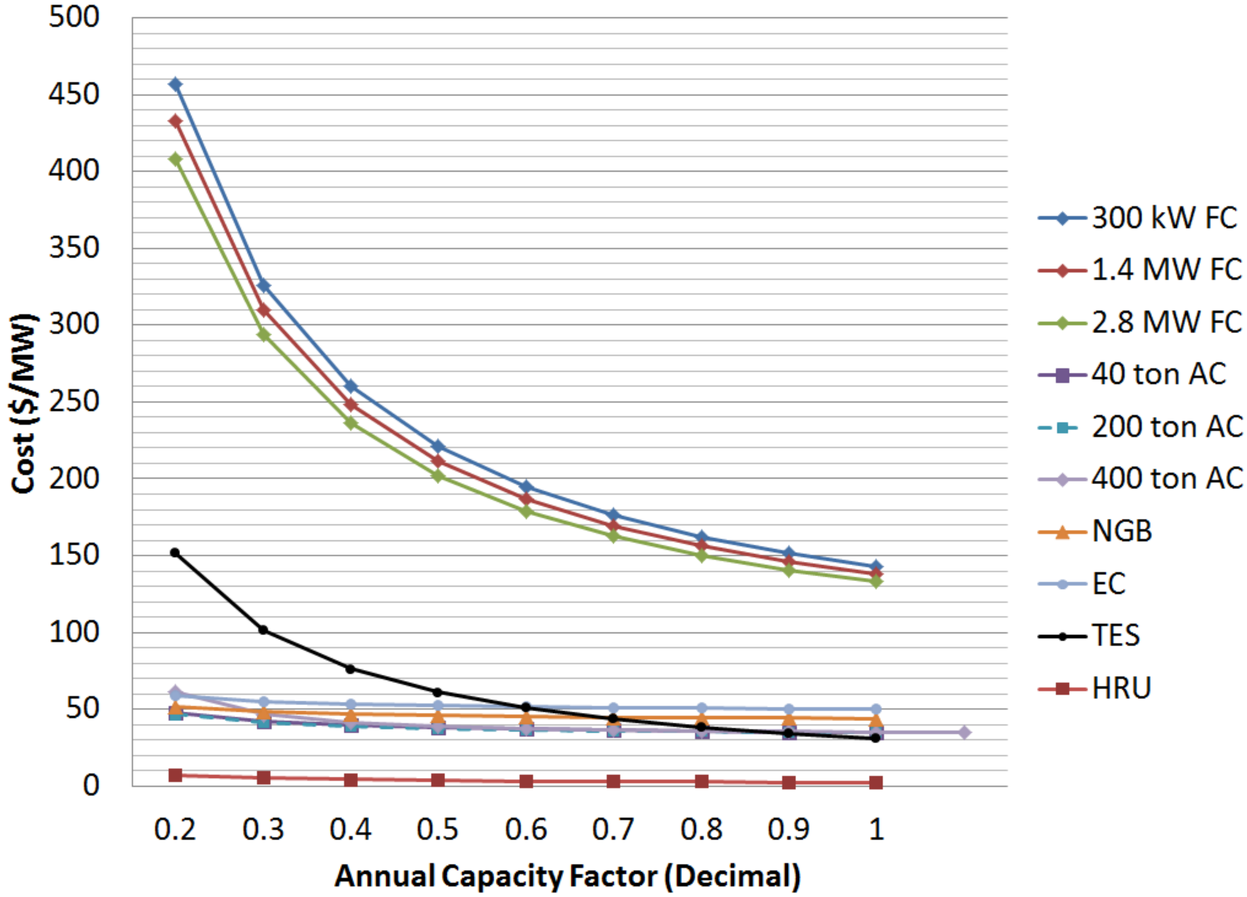

Figure 23: Capacity Factor Sensitivity

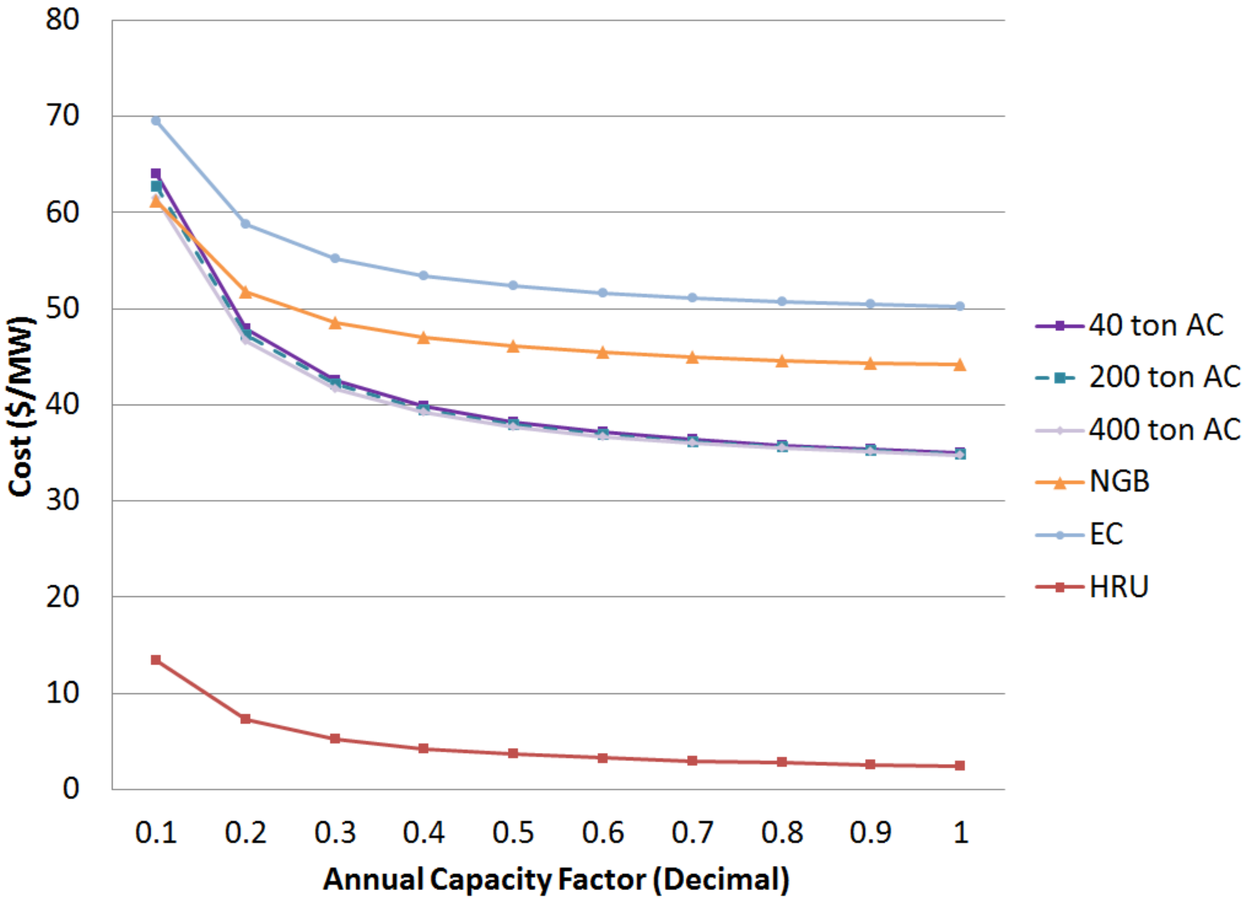

Figure 24: Minor Equipment Capacity Factor Sensitivity

4.3.2 OWNERSHIP TYPE IMPLICATIONS

A set of representative equipment portfolios was chosen to evaluate the effect of ownership type on portfolio LCOE. Ownership type 1 represents a merchant-owned system, ownership type 2 represents an investor-owned utility, and ownership type 3 represents a public-owned utility. The financial assumptions for each of the three ownership types are compared in the Economic Parameters shown in Table 7. The results are summarized in Table 8.

Table 7: Economic Parameter Assumptions for the Three Ownership Types

Ownership Type	Owner	Equity Percent (%)	Return Rate (%)	Loan Interest Rate (%)
1	Merchant	33	13.25	5.91
2	Investor-owned Utility	55	10.04	5.28
3	Public-owned Utility	0	0	3.20

Table 8: Ownership Type Analysis

Portfolio	Building	LCOE (/MWh) Ownership Type 1	LCOE (/MWh) Ownership Type 2	LCOE (/MWh) Ownership Type 3
2.8 MW FC, AC, HRU, EC, NGB	LBVA	$97.5	$97.3	$85.5
300 kW FC, AC, HRU, EC, NGB	MSTB	$122.6	$122.0	$98.4
300 kW FC, AC, HRU, NGB, EC	SCAQMD	$85.3	$84.9	$72.7

Investor-owned utility plants are less expensive than merchant owned plants because of the favorable financing terms available to investor-owned utilities. Public-owned utility plants are the most economical due to their favorable financing terms and investment structure.

4.3.3 FUEL CELL COSTS

The installation cost of a fuel cell is one parameter that may have a significant impact on the levelized cost of electricity (LCOE) of a high temperature fuel cell and absorption chiller (HTFC/AC) portfolio. The economic model used in this analysis uses a variable called the overnight installation cost to account for the upfront cost of the fuel cell. The overnight installation cost is the $/kW price required to purchase and install the fuel cell assuming the fuel cell installation is completed overnight. The code takes the actual installation time into account in determining the overall installed cost of the project, but the overnight cost neglects all costs and escalation incurred during the construction period. This makes for a simple way to compare different equipment purchase prices. Another potentially influential cost component of the fuel cell is the rate associated with its operation and maintenance. The economics model uses a Fixed Operating and Maintenance (FOM) variable to account for these costs. The FOM is the $/kW-yr price the owner must pay for the fuel cell operator to perform activities such as fuel cell start-up after a trip, routine maintenance, and overhauls. Finally, the fuel cell stack life is another variable that could potentially impact the overall LCOE of an HTFC/AC system. The economics code allows the user to specify the number of years that the fuel cell can operate before performance degradation necessitates replacement of the fuel cell stacks. The costs associated with replacing the stacks are added to the portfolio each time the fuel cell stacks are replaced over the 20 year life of the project.

Using the best available data for FuelCell Energy's DFC line of molten carbonate fuel cells, the assumed overnight cost, operation and maintenance cost, and stack life for the three fuel cell size assumed in the economics model are summarized in Table 9.

Table 9: Fuel Cell Cost Assumptions

	300 kW DFC300	**1.4 MW DFC1500**	**2.8 MW DFC3000**
Installation Overnight Cost ($/kW)	3600	3300	3000
Fixed Operation and Maintenance Cost ($/kW-yr)	200	200	200
Stack Life (years)	5	5	5

The parameters in Table 9 are inputs to the G-Matrix file, and can be changed by the user prior to each model run.

The statistical design-of-experiments program Design-Expert 9, version 9.0.1.0 by Stat-Ease Incorporated was used to analyze these three fuel cell cost factors. The Long Beach Veteran's Affairs Hospital was analyzed as a representative building load. The equipment portfolio analyzed includes a 2.8 MW fuel cell, a 400 ton absorption chiller, a heat recovery unit, an electric chiller, and a heat recovery unit. The grid is used for importing electricity demands not met by the fuel cell. A 3 level factorial test was carried out on the three cost factors. Installation overnight cost was varied from $3,000/kW to $6,000/kW, fixed O&M was varied from $200/kW-yr to $400/kW-yr, and stack life was varied from 4 to 6 years investigate how the portfolio's LCOE changed with each of these factors.

Installation cost was the most influential parameter associated with the fuel cell. Fixed operating and maintenance cost was also very influential, but fuel cell stack life had only a marginal effect on the LCOE of the equipment portfolio. Figure 25 shows the half-normal plot of effects. Any factors that lay off of the red line are statistically significant. Though stack-life lays close to the normal line, it was included as a factor in the analysis to see what significance if any, it may have.

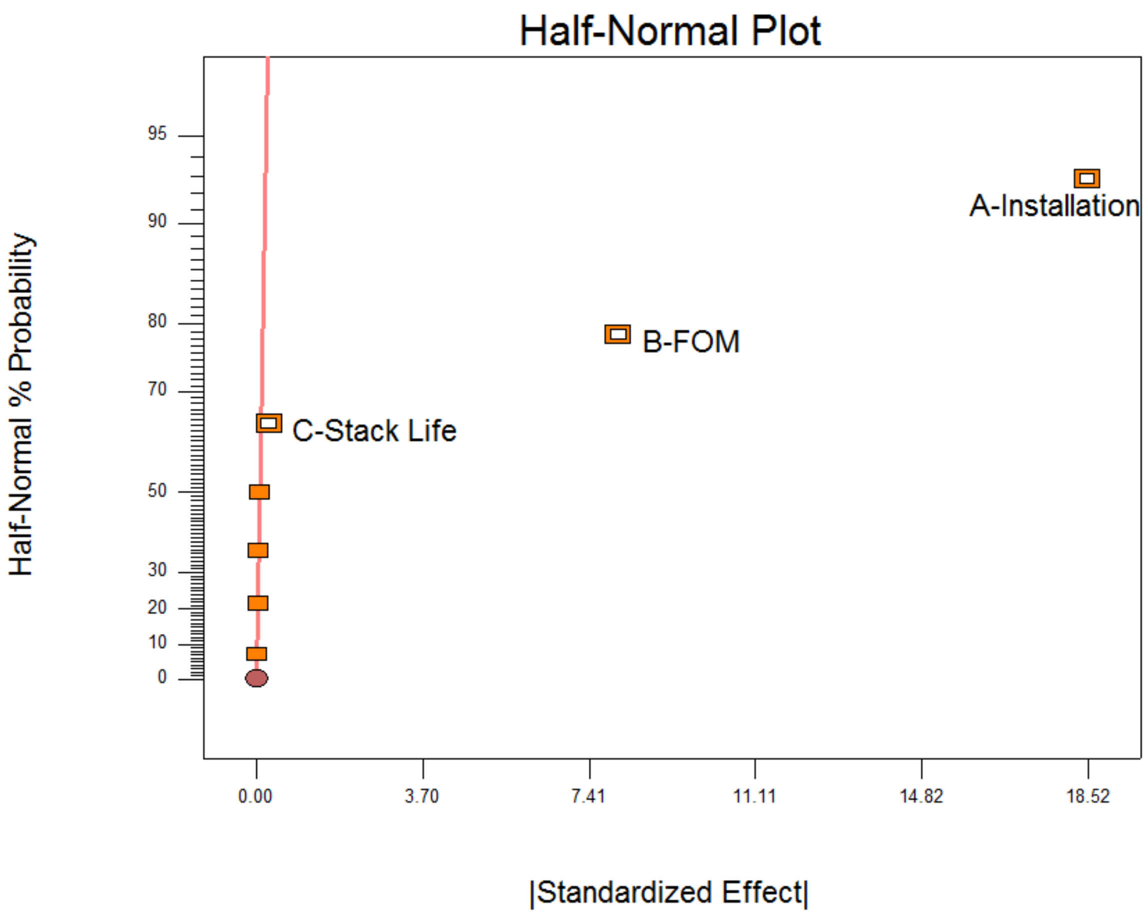

Figure 25: Significant Fuel Cell Cost Factors

Figure 26 shows that the results of the analysis of variance (ANOVA) on the three factor test. The F Value is shows the relative contribution of the model variance compared to the residual variance. A large F value indicates that the model is significant, while a small F value indicates that the impact of the model could be a result of noise. The p-value of each of the factors is less than 0.05 which means that the chance of the model's F value being as high as it is due to noise is less than 5 %. The ANOVA confirms that all three factors are significant.

Response 1 LCOE

ANOVA for selected factorial model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	816.28	3	272.09	61976.87	< 0.0001	significant
A-Installation	*686.04*	*1*	*686.04*	*1.563E+005*	*< 0.0001*	
B-FOM	*130.09*	*1*	*130.09*	*29631.21*	*< 0.0001*	
C-Stack Life	*0.16*	*1*	*0.16*	*36.17*	*0.0039*	
Residual	0.018	4	4.390E-003			
Cor Total	816.30	7				

Figure 26: Fuel Cell Cost Components ANOVA

Figure 27 shows the results of the design of experiments analysis. The largest cost contributor, installation overnight cost, is represented by the left and right corners of the cube. The corners on the left-hand side of the cube represent LCOE associated with $3,000/kW installation rates, while the right-hand side of the cube represents LCOE's associated with $6,000/kW. The portfolio with the smallest LCOE is represented in the bottom, left side of the cube when installation and O&M costs are low.

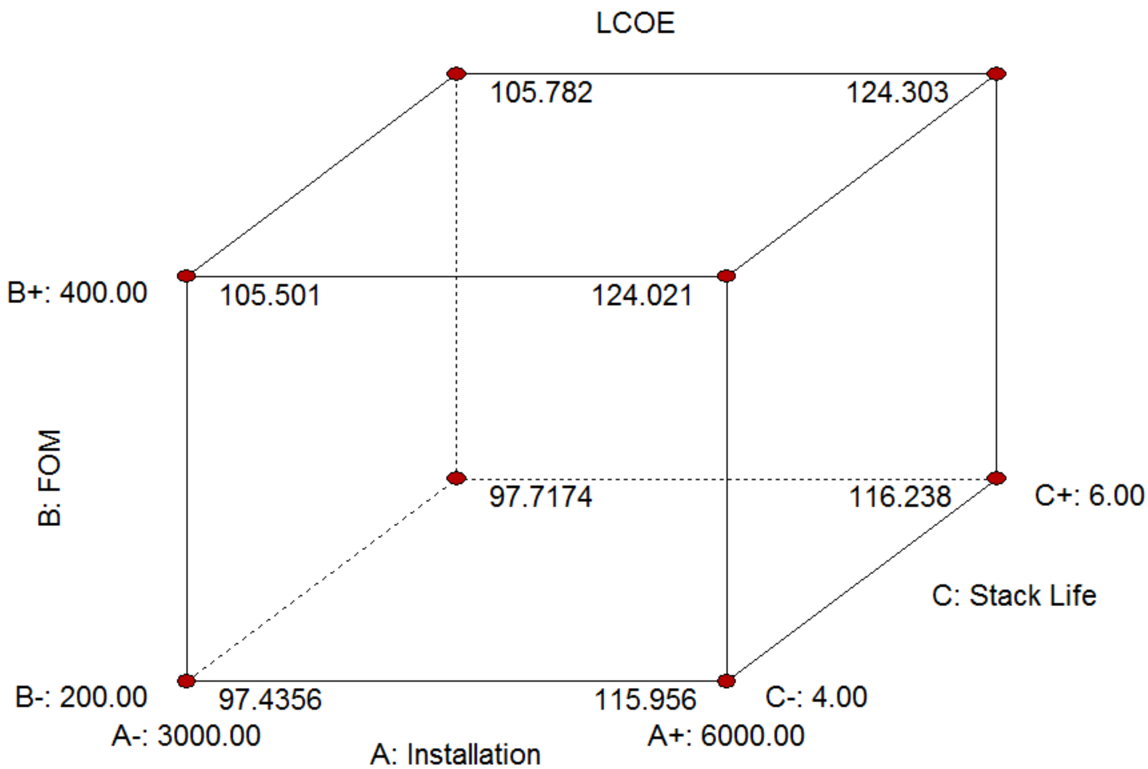

Figure 27: Results of Fuel Cell Cost Factors Sensitivity Test

The results of the fuel cell cost sensitivity analysis can be summarized by the following equations. The first equation represents the LCOE of the portfolio at LBVA in terms of coded factors. Factor magnitudes are normalized to produce coded factors. Coded factors are then used for comparisons between factors to assess their relative importance. *A* represents the coded variable for installation cost, *B* represents the coded variable for FOM, and *C* represents the coded variable for stack life. The second equation represents the LCOE of the portfolio in actual terms (i.e., factors are expressed in actual magnitudes).

Equation 1: LCOE Based on Fuel Cell Cost Factors

$$LCOE = 110.87 + 9.26 * A + 4.03 * B + 0.14 * C$$

$$LCOE = 70.28634 + 0.006174 * Installation + 0.04033 * FOM + 0.14088 * Stack\ Life$$

4.4 EQUIPMENT COST CONTRIBUTIONS

The results in Sections 4.2.1 and 4.2.2 evaluate the breakdown of costs associated with each individual piece of equipment included in the selected portfolio. In order to get a perspective on where those costs are being allocated, the cost code was adjusted to aggregate different cost components across all the equipment in the selected portfolio. Each of the eleven cost components associated with each piece of equipment were categorized into five major LCOE cost categories, as shown in Table 10.

Table 10: Cost Categories

Financing	Taxes	Variable O&M	Fixed O&M	Import/Export
Debt Equity	Ad Valorem State Federal CO_2	Base VOM Transmission Fuel	Base FOM Insurance	Imports/Exports

Figure 28 and Figure 29 show various equipment portfolios at MSTB and LBVA. The bar graphs represent the percentage of levelized costs allocated to each of the five cost categorizes. For the case at MSTB where a majority of the electricity generated by the fuel cell is exported back to the grid, revenues associated exported electricity are inverted across the x-axis in order to facilitate comparison with the other cost components. The LBVA scenario is importing a majority of its electricity, so the costs associated with electric imports are naturally the same orientation as the other costs.

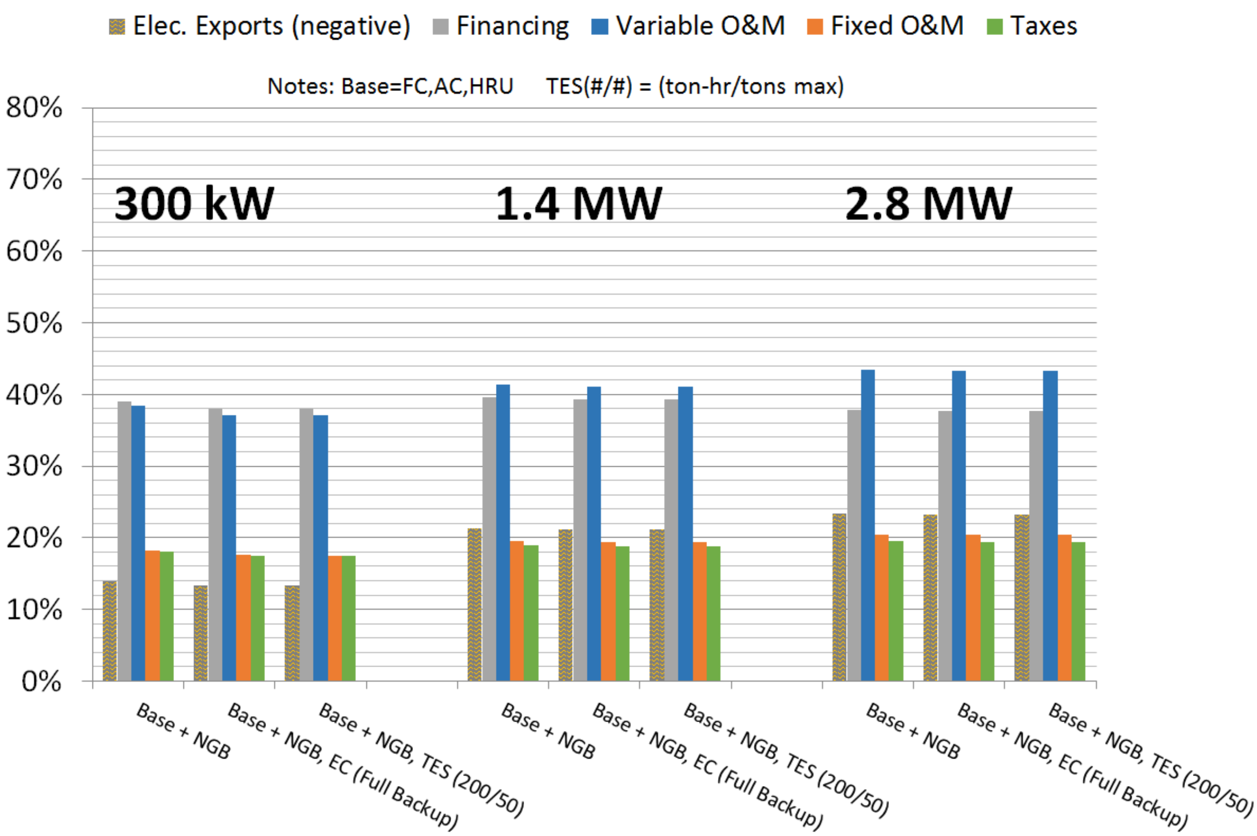

Figure 28: Levelized Cost Allocations by Percentile at MSTB

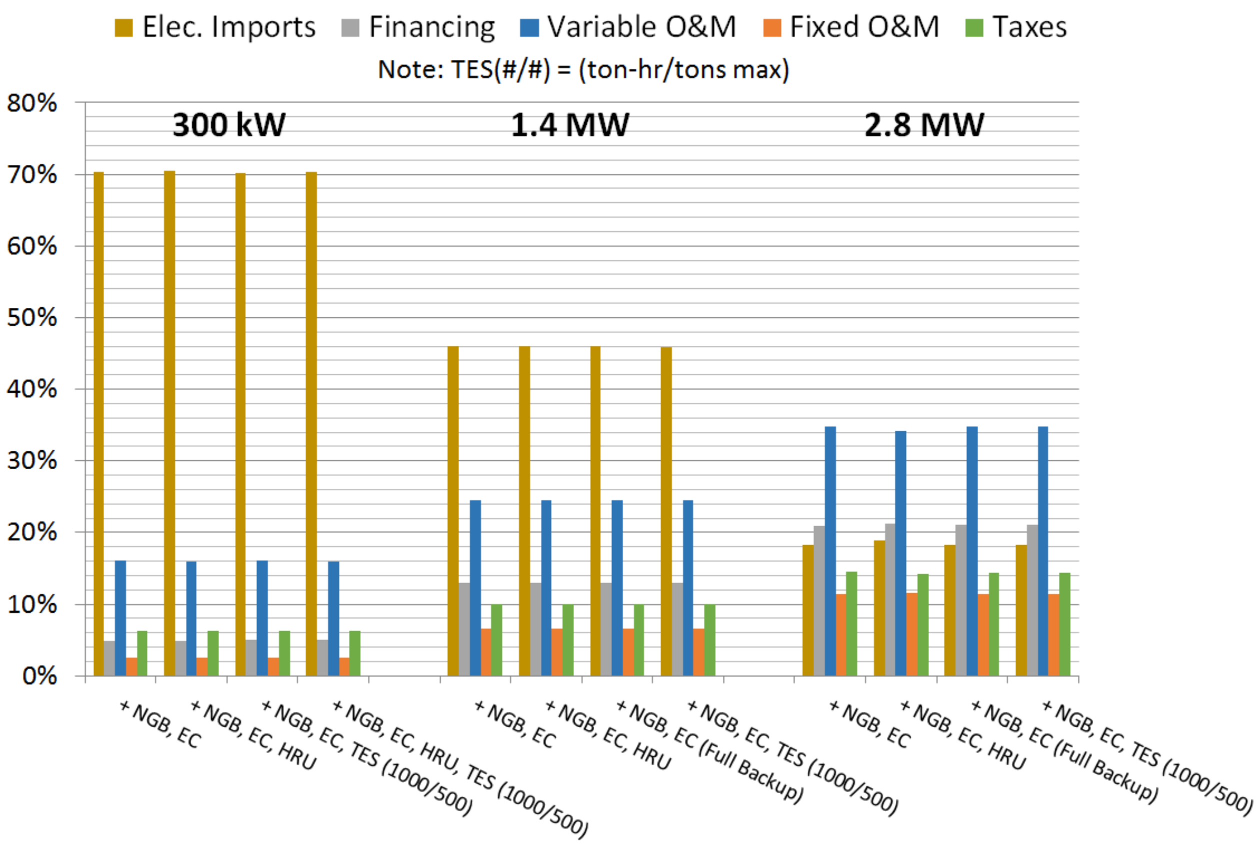

Figure 29: Levelized Cost Allocations by Percentile at LBVA

It is apparent from Figure 28 that costs allocated to financing and variable O&M are the primary cost drivers for a fuel cell system at MSTB, an installation that is exporting a majority of its electricity. As the fuel cell size is increased from left to right, the returns from exporting electricity grow, the percentage of LCOE allocated to installation decreases, and the percentage of costs allocated to variable operating and maintenance grow substantially.

The results of the analysis performed on the LBVA hospital tells a different story as it represents an HTFC/AC system that is more closely sized to the demand of the building being served. The percent of LCOE allocated to financing, variable and fixed O&M, and taxes each scale up with increased fuel cell size while the LCOE percentage allocated to importing electricity decreases dramatically as expected.

Variable O&M costs are the largest LCOE contributors other than electricity imports in each scenario evaluated. A rate of $0.21/MWh was assumed based on best available industry data. A reduction in this rate by increased market penetration or improved O&M techniques would have a very positive impact on the financial viability of such systems.

Another major cost component is financing. Each of the scenarios assessed assumes 33% equity with a 13.25% required rate of return, and 5.91% loan interest, which are the same values as those assumed in the California Energy Commission's Cost of Generation Model 3.62. A reduction in equity return or interest rates would have a large impact on the LCOE of a fuel cell system such as the ones analyzed here.

4.5 SENSITIVITY ANALYSIS OF KEY MODEL ASSUMPTIONS

To build upon the high temperature fuel cell and absorption chiller (HTFC/AC) system economic insight derived from previous sections of this thesis, a two-part sensitivity analysis was carried out on the input assumptions made during construction of the integrated economics and technical model. Various engineering and financial assumptions were evaluated in order to characterize the importance of deviations from the assumptions in a real-world HTFC/AC deployment. The analysis focused on an equipment portfolio consisting of a fuel cell, absorption chiller, heat recovery unit, natural gas boiler, electric chiller and grid imports and exports and used the Long Beach Veteran's Affair's (LBVA) hospital as a representative installation building. The fuel cell is run at base load capacity, with any extra generation exported to the grid. The grid is also used to support any electricity loads not met by the fuel cell. The first portion of the sensitivity analysis varies the magnitude of each of the numerical input factors by +/- 10% in order to perform a perturbation analysis (DOE 1). The second portion of the sensitivity analysis deals with the impact of future changes in HTFC/AC technology and utility prices by using predictions of future factor values (DOE 2).

4.5.1 RESPONSES CONSIDERED

The perturbation analysis (DOE 1) and the future scenario analysis (DOE 2) evaluate the responses listed in

Table 11.

Table 11: Sensitivity Analysis Responses

Response	Units	Application
Levelized Cost of Electricity	$/MWh	DOE 1 & DOE 2
CO_2 Produced	Short tons over 20 years	DOE 1 & DOE 2
CO_2 Saved	Short tons per year	DOE 2
Savings	$/MWh	DOE 2

Levelized cost of electricity (LCOE) refers to the constant annual cost that is equivalent on a present value basis to the actual annual costs of electricity. Refer to Section 4.1.5 for a more detailed description of LCOE.

The integrated economic and technical model calculates fuel cell CO_2 production by multiplying the fuel cell's natural gas flow rate (MMBtu/hr) by and a conversion factor which correlates the CO_2 produced by the fuel cell with MWh of energy produced at the rated 47% fuel to electricity conversion efficiency. CO_2 emissions from imported electricity are included by multiplying the US Environmental Protection Agency National Average CO_2 emission rate for conventional natural gas plants of 1135 lb/MWh [13] by the total megawatt-hours of electricity imported. Emissions from parasitic loads are not considered by the model. Since the rate of CO_2 production is higher on a per MWh basis for a conventional natural gas plant, CO_2 emissions for the overall service of the building are reduced with increased utilization of the fuel cell.

Savings and CO_2 emissions reduced (saved) were added to the results for DOE 2. Both values are calculated based on a competing system consisting of grid imported electricity, a natural gas boiler, and an electric chiller. Savings is the $/MWh difference between the competing scenario and the HTFC/AC scenario given the same electricity and natural gas price inputs. CO_2 Saved represents the short tons of CO_2 emissions not emitted (reduced) per year when the HTFC/AC system takes the place of the competing system.

4.5.2 FACTORS EVALUATED

The economic results presented in previous sections of this thesis were focused on evaluating different equipment portfolios and other major variables which directly impact the Levelized Cost of Electricity (LCOE) of an HTFC/AC system. The goal of the sensitivity analysis is to dive into the details of the economic model and evaluate the relative impacts of a broad range of assumptions and their interactions. Nine different input factors were varied in order to evaluate their impact on different model responses.

Seven continuous numerical factors were considered as shown in Table 12, along with two categorical factors, which are shown in Table 13. DOE 1 uses the default values for the numeric factors (ref. Section 4.1.1) and varies them by +/-10% to perform the perturbation analysis. In

DOE 2, the numeric factors were assigned a range from the Minimum to Maximum as shown in Table 12.

Table 12: Numerical Factors

Factor Code	**Factor**	**Units**	**Default (DOE 1)**	**Minimum (DOE 2)**	**Maximum (DOE 2)**
A	Fuel Cell Efficiency	%	47	45	60
B	Absorption Chiller Coefficient of Performance	N/A	1.28	0.8	1.8
C	Parasitic Load	%	10	5	20
D	CO_2 Price	$/Ton	20	0	40
E	Natural Gas Price	$/MMBTU	5	2.5	10
F	Electricity Import Price	$/MWhr	120	120	240
G	Electricity Export Rate	$/MWhr	30	0	60

Table 13: Categorical Factors

Factor Code	**Factor**	**Units**	**Level 1 (DOE 1 & 2)**	**Level 2 (DOE 1 & 2)**	**Level 3 (DOE 1 & 2)**
H	Fuel Cell Size	kW	300	1400	2800
J	Ownership Type	N/A	1 Merchant Owned	2 Investor-Owned Utility	3 Public-Owned Utility

The model simulates FuelCell Energy's DFC line of molten carbonate fuel cells which range from 300 kW to 2.8 MW capacities (Ref. Section 2.8.1). The published thermal-to-electric efficiency of the fuel cell line is 47%. DOE 2 considers a low-end efficiency just below the published value at 45% in order to evaluate the impact of a slightly degraded fuel cell stack. FuelCell Energy has recently developed system concepts to further increase the net electric efficiency of their DFC line to 60% by placing the fuel cell stacks in series and achieving very high utilization factors [31]. Some solid oxide fuel cell systems have also shown fuel-to-electricity conversion efficiencies approaching 60%. A maximum fuel cell efficiency of 60% is considered in DOE 2 in order to evaluate the financial impact of this improved efficiency.

The absorption chiller modeled in the economics code is a direct exhaust fired BROAD U.S.A. double effect lithium bromide chiller (Ref. Section 2.8.2). The rated coefficient of performance (COP) of the BROAD line of absorption chillers is 1.28. A typical double effect absorption chiller reaches a COP of 1.0, and they are known to be very sensitive to operating conditions so it is not uncommon for them to operate well below their rated COP [24]. Therefore, DOE 2 evaluates a low-end COP of 0.8 to simulate a typical chiller operating at 80% of its rated COP. Triple effect chillers, though not widely commercially available at this time, have the potential to reach COPs in the range of 1.4 to 1.8 [24, 25]. A high-end COP of 1.8 is modeled in DOE 2 to see what effect there will be on the system if a triple effect absorption chiller were installed.

Parasitic loads are simplistically modelled in the economics code as a set percentage of fuel cell output. It is very difficult to estimate the electricity required to power all of the auxiliary loads of an HTFC/AC system because they will vary with installation. For example, the size of pump that is installed to supply the building with chilled water will be a result of the size and length of piping selected, as well as the flow and temperature requirements of the system. A parasitic power fraction of 10% is assumed in typical model runs. For sensitivity analysis DOE 2, this value is cut in half to simulate the lowest anticipated parasitic loads, and doubled to simulate the worst case scenario.

CO_2 price is the \$/ton-CO_2 value assigned to any CO_2 produced as a result of serving the heating, cooling, and power loads of the building. Emissions could come from the fuel cell, the natural gas boiler, or from the grid when it provides imported electricity to the building or auxiliary equipment. The CO_2 price in California is currently \$13/ton [26]. The California Energy Commission's Cost of Generation Model 3.62 predicts that the price of CO_2 will rise to \$135/ton in 25 years. A CO_2 price of \$20/ton is generally assumed in previous sections of this thesis in order for the evaluations to be applicable to near-term, future HTFC/AC installations. The sensitivity analysis carried out in this section considers a range of CO_2 prices. For DOE 2, the low-end considers no CO_2 taxes. This simulates the HTFC/AC installation occurring in a region without an established market for carbon trading. On the high-end for DOE 2, CO_2 price is assumed to be \$40/ton to simulate a scenario in which prices are double that of the previous evaluations in this thesis.

The price for natural gas purchased for a small commercial building through the Southern California Gas Company in January 1, 2015 is \$6.32/MMBtu, down 14.6% from December 1, 2014 [30]. A natural gas price of \$5/MMBtu is assumed in previous sections of this thesis in order for the evaluations to reflect even lower prices in the near-term future. For DOE 2, the natural gas price was varied from \$2.5 to \$10/MMBtu to simulate conditions should the price of gas decrease or increase by a factor of two.

The average electricity price for the University of California, Irvine Medical Center was $130/MWh in 2014 [31]. An electricity import price of $120/MWh is assumed in previous sections of this thesis in order for the HTFC/AC levelized cost of electricity comparisons to be conservative relative to the competing scenario. For DOE 2, the electricity import rate was varied from $120 to $240/MWh to simulate conditions for the case when the price of electricity increases by a factor of two relative to the base case scenarios.

It is typical for electric service providers to discourage distributed generation owners from exporting electricity back to the grid, as the existing infrastructure is typically not designed to handle reverse power flow. This is especially the case when the amount of electricity being exported is constantly varying. On the other hand, there is a possibility that returns on exported electricity can become a reality in the near future as distributed generation becomes more common and as the electricity grid of the United States gets updated to accommodate the associated changes in load and generation patterns. Smart Grid innovations may play a big role in supporting the introduction of more distributed and renewable power generation that can be exported to the grid. Therefore, DOE 2 considers a range of export returns from zero up to $30/MWh. In an effort to obtain a conservative result, a high-end return rate of $30/MWh was chosen as it is one-quarter of the typically assumed imported electricity rate.

While ownership type was individually evaluated in Section 4.3.2 of this thesis, it was included in this sensitivity analysis to evaluate any interactions it may have with other factors.

4.5.3 DESIGN OF EXPERIMENTS (DOE)

The statistical design-of-experiments (DOE) program Design-Expert 9, version 9.0.1.0 by Stat-Ease Incorporated was used to optimize an experiment that uses the least number of model runs possible to fully characterize each of the factors and second order interactions. Two categoric factors which have three levels each and seven continuous factors require seventy-two model runs to be fully characterized. Extra model runs for lack of fit were not included because the Matlab® model being analyzed is not subject to experimental error. The DOE software creates a nine column array where each of the rows represents a single model run. The array is exported to an Excel file and saved as Inputs.xlsx in the economics code folder so it can be referenced by the Run code in order to populate the inputs matrix. The integrated economics and technical model writes the results of each of the seventy-two model runs into the results file entitled sensitivity_analysis_results.xlsx. This output file is uploaded back into the DOE software to perform the analysis. An ANOVA was performed on each of the responses, and the model terms were individually checked for significance. Sections 4.5.4 and 0 review the results of each of the sensitivity analyses.

Table 14: Design of Experiments

Design Summary				
File Version	9.0.1.0			
Study Type	Response Surface		**Runs**	72
Design Type	I-optimal	Coordinate Exchange	**Blocks**	No Blocks
Design Model	Quadratic		**Build Time (ms)**	326500

The numerical result of each DOE is a predictive model for each response. The model is written in the form of an equation which sums the products of each of the factor inputs and their respective regression coefficients. In the post-ANOVA phase of the analysis, the predictive model is created in both actual and coded terms. Coded terms set the minimum value of the input factor to -1 and the maximum value to +1. Coding eliminates the factor's units and visually gives equal weight to each factor regardless of its magnitude. For the coded predictive model equation, the coefficient represents the change in the response as the factor level is changed by one coded unit.

4.5.4 RESULTS OF PERTURBATION ANALYSIS (DOE 1)

A perturbation analysis (DOE 1) was performed by varying the nominal values of each numeric factor by +/-10%. Table 15 shows the factor statistics and Table 16 shows the response statistics for DOE 1.

Table 15: Test 1 Factor Statistics

Factor	Name	Units	Type	Min.	Max	Coded Values		Mean	Std. Dev.
A	FC Eff	%	Numeric	42.3	51.7	-1=42.3	1=51.7	46.93	3.99
B	AC COP		Numeric	1.15	1.41	-1=1.15	1=1.41	1.28	0.11
C	Parasitic Load %		Numeric	9	11	-1=9	1=11	10.00	0.85
D	CO2 Price	$/short ton	Numeric	18	22	-1=18	1=22	20.06	1.73
E	NG Price	$/MMBtu	Numeric	4.5	5.50	-1=4.5	1=5.5	5.00	0.43
F	Import Rate	$/MWh	Numeric	108	132	-1=108	1=132	120.1	10.11
G	Export Rate	$/MWh	Numeric	27	33	-1=27	1=33	29.99	2.52
H	FC Size		Categoric	300	2800			**Levels:**	3
J	Ownership		Categoric	1	3			**Levels:**	3

Table 16: Test 1 Response Statistics

Response	Name	Units	Analysis	Min.	Max	Mean	Std. Dev.
R1	LCOE	$/MWh	Polynomial	80.61	108.58	97.40	6.05
R2	Total CO2	Short tons	Polynomial	423945	487309	46888	18817

Table 17 shows the predictive LCOE model coefficients in terms of coded factors. Interaction terms are neglected due to the number of terms and their relative insignificance. The most influential factor in calculating the LCOE of a HTFC/AC system at a representative hospital such as LBVA is the imported electricity rate (F). The price of electricity from the grid is 45% more important than any other factor in the model. The factor with the next most significance on LCOE is ownership type. When ownership type 1 (J[1]) is selected, the portfolio LCOE is increased by a coded factor of +2.79, and when ownership type 3 (J[2]) is selected the portfolio LCOE is increased by +2.51 in coded factors. Fuel cell size (H) is the next most influential factor, followed by natural gas price (E), fuel cell efficiency (A), CO_2 price (D), and parasitic load percent (C).

Table 17: DOE 1 LCOE Coded Coefficients

Term	Coefficient Estimate
Intercept	97
F-Import Rate	4.1
J[1]-Ownership Type Low	2.8
H[1]-FC Size Low	2.6
J[2]-Ownership Type High	2.5
E-NG Price	1.8
D-CO2 Price	0.85
H[2]- FC Size High	0.68
C-Parasitic Load %	0.36
B-AC COP	0.03
G-Export Rate	-0.01
A-FC Efficiency	-1

The perturbation plots shown in Figure 30 graphically represent the numerical factors and their relationship with LCOE. Ownership type is set to 1 to represent a Merchant-Owned plant, but the shape of the perturbation plots apply to each ownership type. Having different ownership conditions would only scale the plots. The bar graph shown in Figure 31 shows the relationship between the categoric factors and LCOE when the numeric factors are set to their default values. LCOE is minimized when the imported electricity rate is low, the fuel cell is large, and the owner is a public-owned utility.

It is apparent from this analysis that the imported electricity rate estimated during model creation will significantly alter the results of the analysis, especially when one of the smaller HTFC/AC portfolios is being considered. This makes sense since the average power demand of the hospital is 3.5 MW so the larger the HTFC/AC portfolio, the less the hospital will rely on imported electricity. The estimated value for fuel cell efficiency only significantly affects the larger fuel cell systems as there is less reliance on grid energy and the operation of the fuel cell is more important. The same holds true for natural gas price.

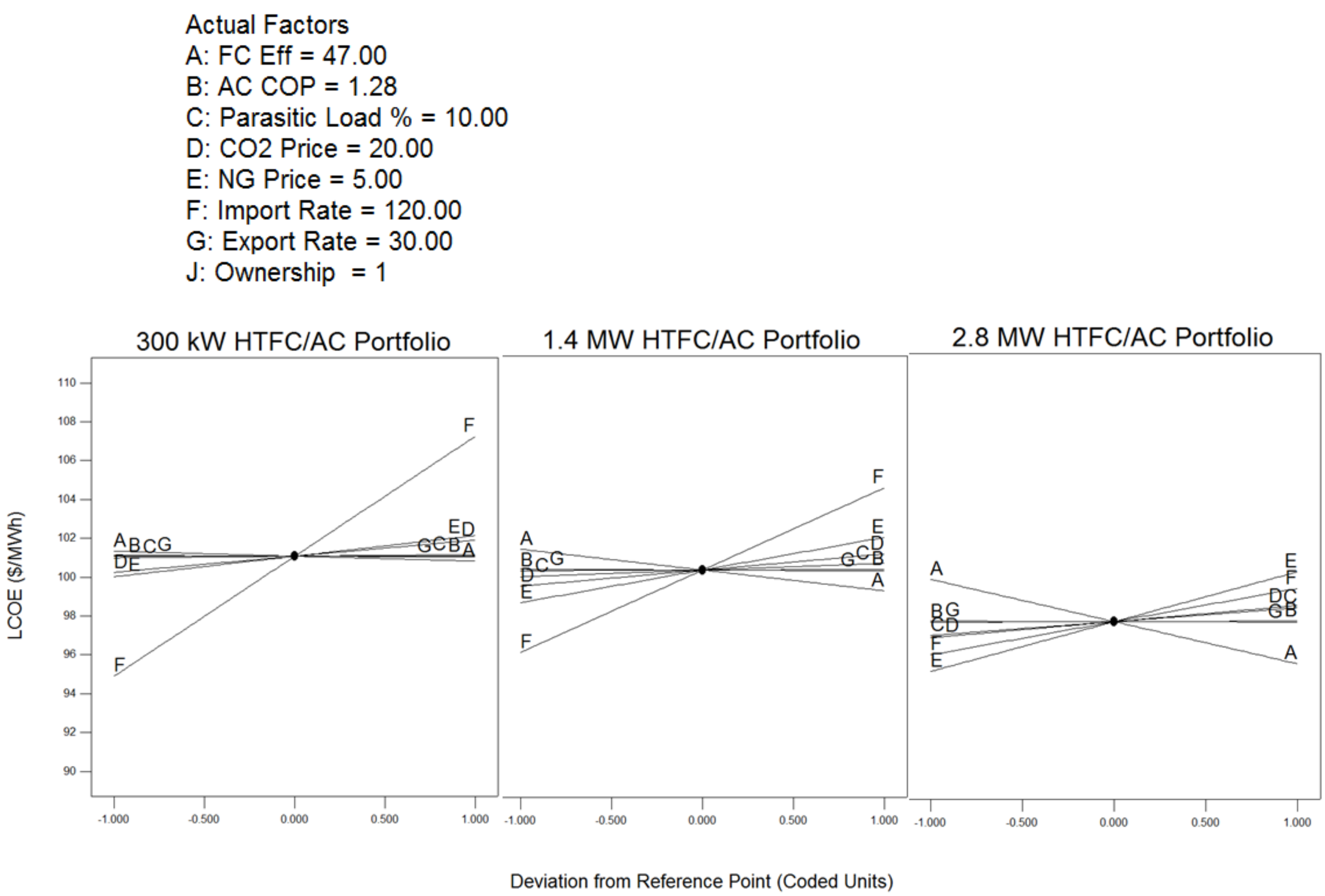

Figure 30: LCOE: Perturbation of Numeric Factors in DOE 1

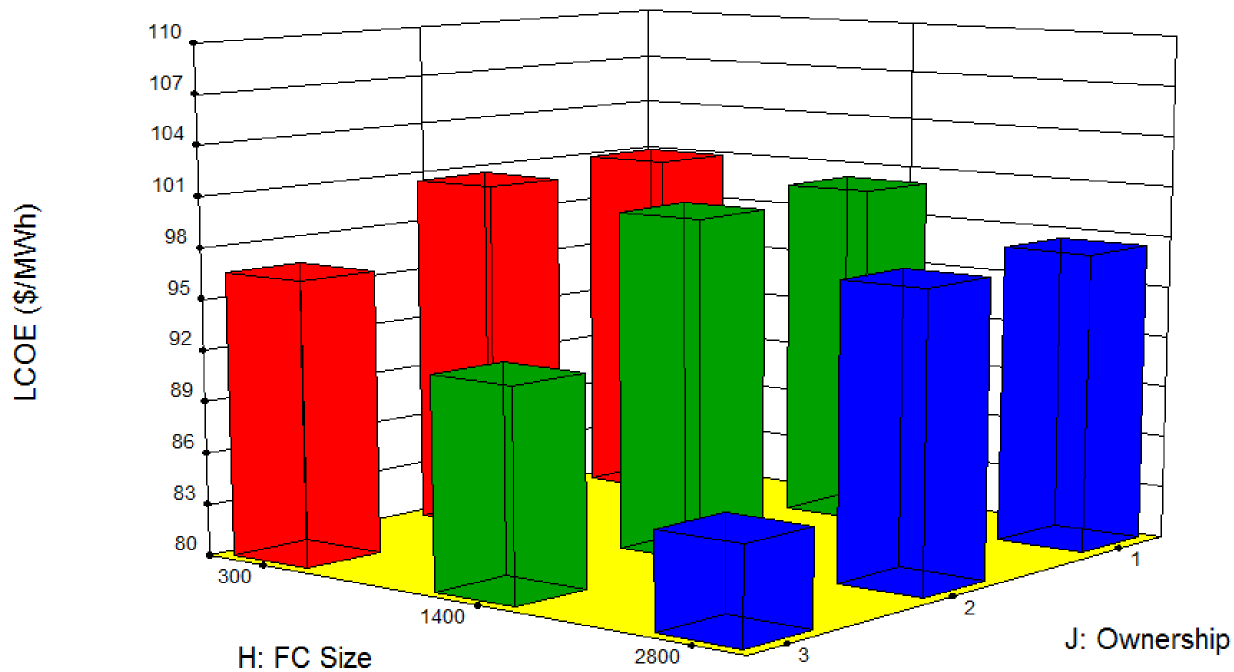

Figure 31: LCOE: Perturbation of Categoric Factors in DOE 1

Table 18 shows the final predictive CO_2 emissions model coefficients in terms of coded factors. Interaction terms are included as they play an important role in CO_2 emissions. The effects of CO_2 price, Natural Gas Price, Import Rate, Export Rate, and Ownership Type factors and their interactions were excluded from the CO_2 model. Therefore, the only factors under consideration were the fuel cell size, fuel cell efficiency, and absorption chiller coefficient of performance (COP). The most influential term in calculating the CO_2 emissions of a HTFC/AC system at LBVA is the fuel cell size (H), with a larger fuel cell leading to lower over-all CO_2 emissions. The next most influential parameter is fuel cell efficiency (A), followed by the interaction between fuel cell size and efficiency (AH). The perturbation plots shown in Figure 32 represent the interaction of the three components of CO_2 emissions.

Table 18: DOE 1 CO_2 Coded Coefficients

Term	Coded Coefficient Estimate
Intercept	469,500
H[1]-Fuel Cell Size Low	14,524
AH[1]	10,478
C-Parasitic Load %	2,063
H[2] -Fuel Cell Size High	1,163
BH[1]	1,041
AH[2]	822
BH[2]	54
AC	-18
AB	-31
BC	-151
CH[2]	-195
B-AC COP	-1,313
CH[1]	-1,672
A-FC Eff	-13,103

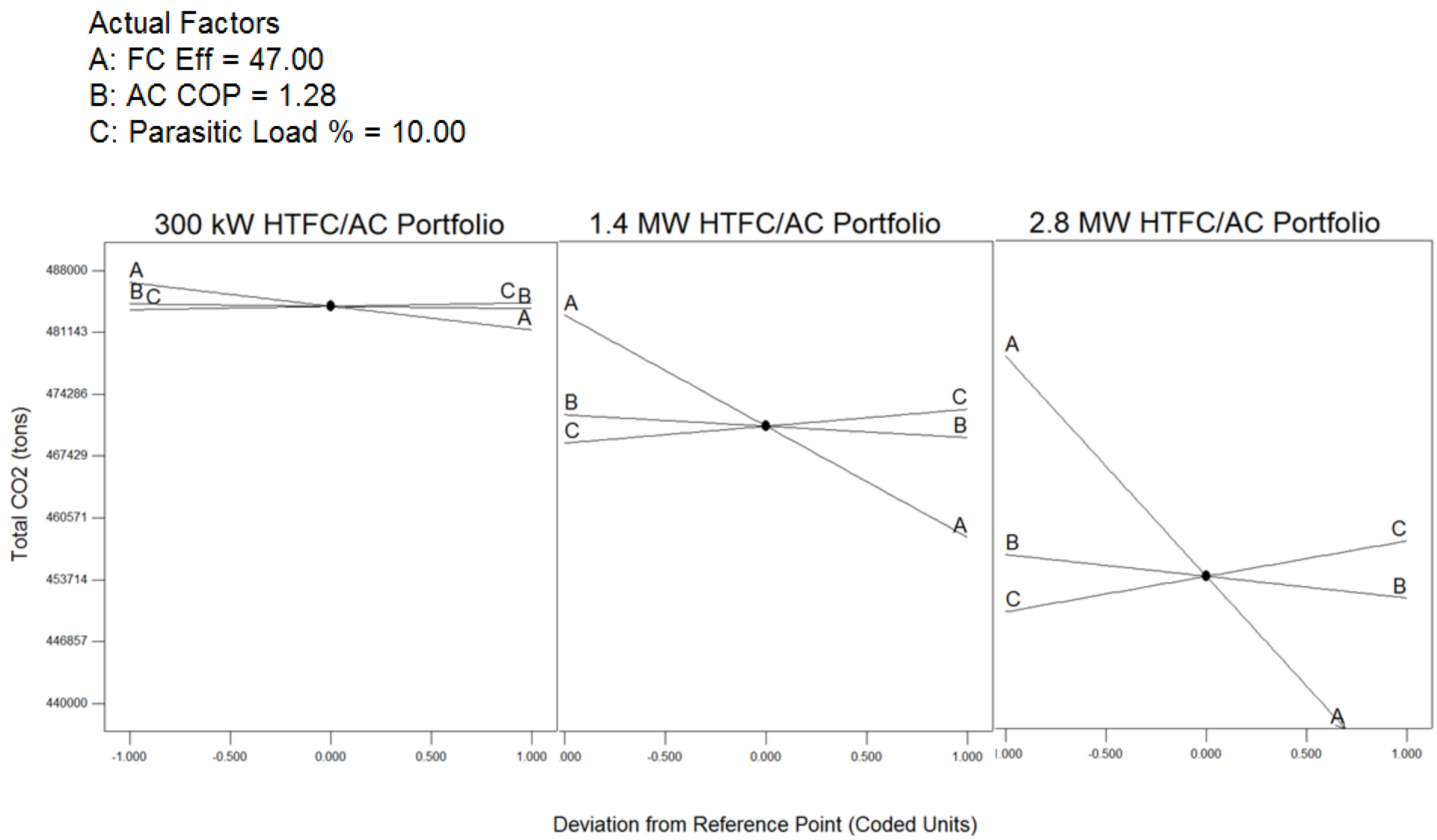

Figure 32: Perturbation Results for Total CO_2 Over 20 Years, DOE 1

4.5.5 RESULTS OF FUTURE SCENARIOS ANALYSIS (DOE 2)

A sensitivity test was performed (DOE 2) to evaluate the impact of future HTFC/AC system scenarios. Values for factors were selected based on predictions of future HTFC/AC technology advancements and utility rates (reference Section 4.5.2). Table 19 shows the factor statistics for DOE 2, and Table 20 shows the response statistics.

Table 19: DOE 2 Factor Statistics

Factor	Name	Units	Type	Min.	Max	Coded Values		Mean	Std. Dev.
A	FC Eff	%	Numeric	45.00	60.00	-1=45	1=60	52.41	6.44
B	AC COP		Numeric	0.80	1.80	-1=0.8	1=1.8	1.29	0.43
C	Parasitic Load %		Numeric	5.00	20.00	-1=5	1=20	12.15	6.31
D	CO2 Price	$/short ton	Numeric	0.00	40.00	-1=0	1=40	20.79	17.2
E	NG Price	$/ MMBtu	Numeric	2.50	10.00	-1=2.5	1=10	6.31	3.13
F	Import Rate	$/MWh	Numeric	120	240	-1=120	1=240	182.27	51.6
G	Export Rate	$/MWh	Numeric	0.00	60.00	-1=0	1=60	28.70	25.3
H	FC Size		Categoric	300	2800			**Levels:**	3
J	Ownership		Categoric	1	3			**Levels:**	3

Table 20: DOE 2 Response Statistics

Response	Units	Minimum	Maximum	Mean	Std. Dev.
LCOE	$/ MWh	69.0652	181.13	121.63	25.67
Total CO_2	Short tons	37,2161	509,422	460,151	29,533
Savings	$/ MWh	-20.26	-92.03	20.07	22.09
CO_2 Saved	Short tons/ year	256.67	7,119.73	2,720.24	1,476.64

Table 21: DOE 1 versus DOE 2 LCOE Coded Coefficients

LCOE	Coded Coefficients			
Term	**+/-10% Variation (DOE 1)**	**Future Scenarios (DOE 2)**	**Percent Change**	**Delta (DOE 1 – DOE 2)**
Intercept	96.90	121.57	25%	-
A-FC Efficiency	-1.14	-1.80	58%	-0.66
B-AC COP	0.03	-0.04	-233%	-0.06
C-Parasitic Load %	0.36	3.98	1006%	3.62
D-CO2 Price	0.85	8.35	882%	7.50
E-NG Price	1.77	12.56	609%	10.79
F-Import Rate	4.06	20.80	412%	16.74
G-Export Rate	-0.01	0.10	-1,391%	0.11

Table 22: DOE 1 versus DOE 2 CO_2 Coded Coefficients

CO_2	**Coded Coefficients**			
Term	+/-10% Variation (DOE 1)	Future Scenarios (DOE 2)	Percent Change	Delta (DOE 1 – DOE 2)
Intercept	469,500	461,701	-2%	-7,799
A-FC Efficiency	-13,103	-16,931	29%	-3,828
B-AC COP	-1,313	-5,119	290%	-3,806
C-Parasitic Load %	2,063	14,810	618%	12,747
AB	-31	5.8	-119%	37
AC	-18	-56	212%	-38
BC	-151	-276	83%	-125

Actual Factors
A: FC Eff = 47.00
B: AC COP = 1.28
C: Parasitic Load % = 10.00
D: CO2 Price = 20.00
E: NG Price = 5.00
F: Import Rate = 120.00
G: Export Rate = 30.00
J: Ownership = 1

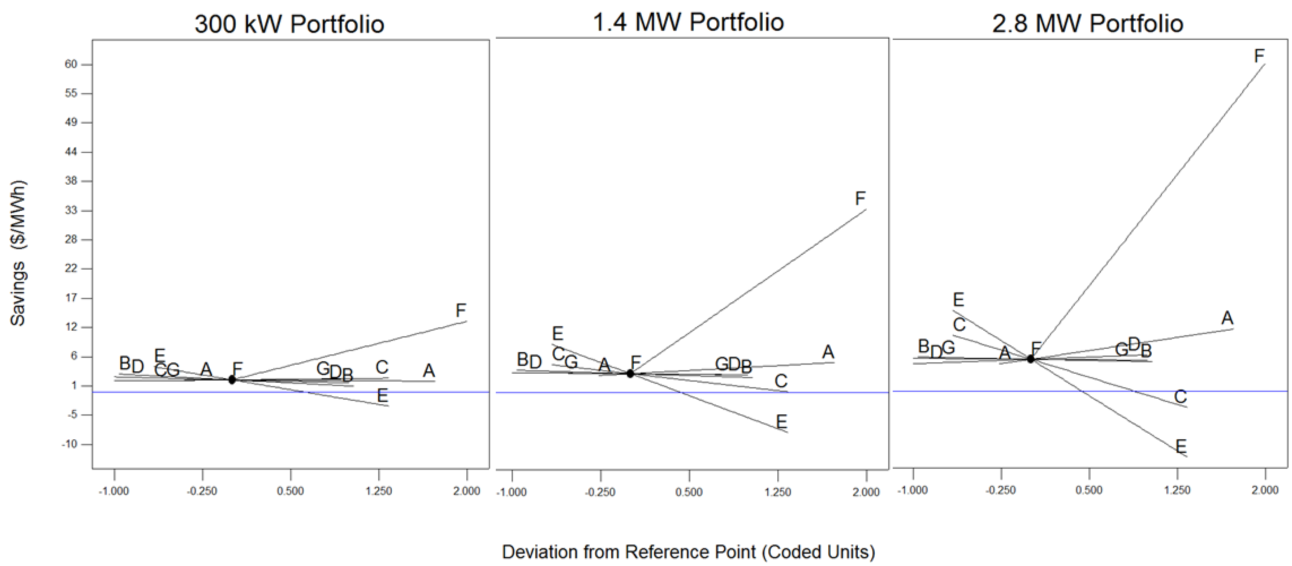

Figure 33: Perturbation Results for Savings, DOE 2

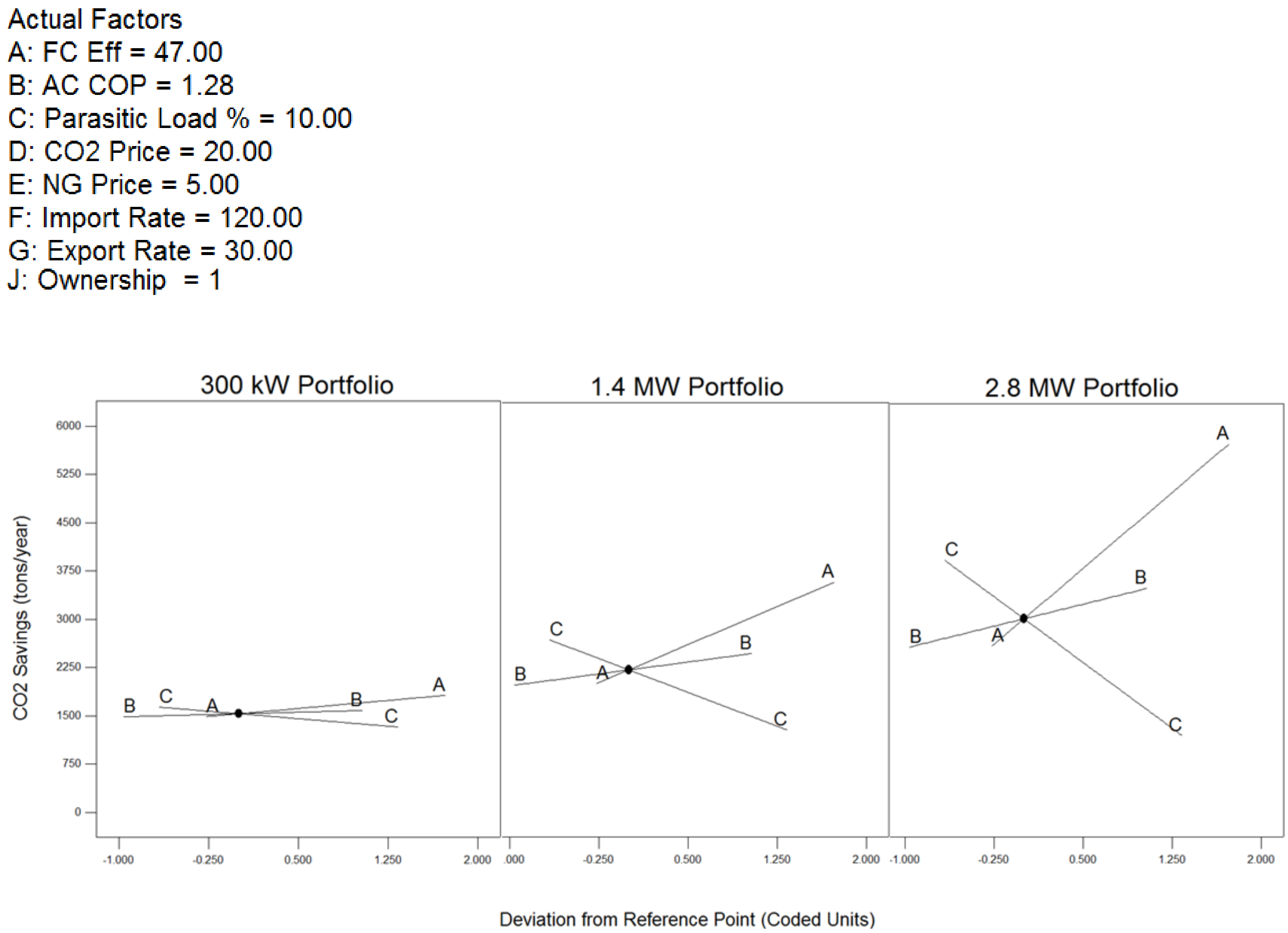

Figure 34: Perturbation Results for CO_2 Saved over 20 Years, DOE 2

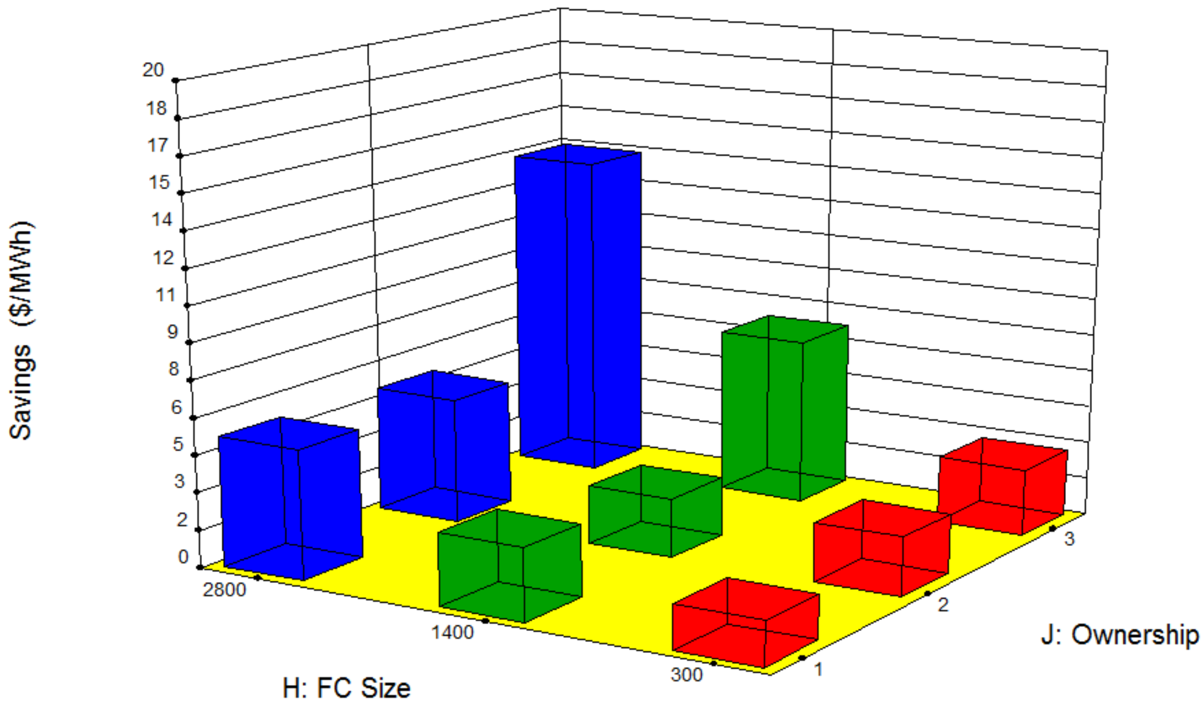

Figure 35: Ownership Type Magnification of DOE 2

4.6 FUTURE WORK

This second generation of the integrated economic and technical HTFC/AC code fulfills the purpose of generating broad cost predictions for various HTFC/AC deployment scenarios. While the code is sufficient to identify trends in portfolio LCOEs, there are several areas in which the technical and economic models could be enhanced to more accurately simulate the physical and financial happenings of a particular HTFC/AC deployment. The following sections detail these potential areas for improvement.

4.6.1 FUEL CELL

In the dispatch code, the fuel cell is currently assumed to be base-loaded and operating at steady state. While this is a fair assumption for many grid-connected stationary power applications, the cost model and the distributed generation dispatch model are structured in order to accommodate load-following. In order to realize the full potential of the program, the fuel cell dispatch code could be modified to follow the load demand curve, shave peak loads, or perform other dispatch logic schemes with appropriate physical constraints and limitations on the dynamic dispatch capabilities of fuel cell systems.

4.6.2 COOLING LOSSES

In the current dispatch, if more cooling is produced than can be supplied to the building or stored in the TES tank, it is discarded. This is the most straightforward way to avoid feedback, but it could be modified to better reflect reality by changing chilled water return temperatures.

4.6.3 VERIFICATION

Perhaps the most important task that remains is to verify and tune the model with real operating and cost data. A first step will be gathering data from the installation at the UCIMC and testing that data against model predictions. This activity is expected to commence in July, 2015.

5 TASK 2 RESULTS

Task 2: Create a technology transfer platform for high temperature fuel cell and absorption chiller systems using the University of California, Irvine Medical Center installation.

5.1 PURPOSE OF THE TECHNOLOGY TRANSFER SHOWCASE

The High Temperature Fuel Cell and Absorption Chiller (HTFC/AC) installation at the University of California, Irvine Medical Center (UCIMC) is designed to enable HTFC/AC technology in the distributed generation market by demonstrating a real-world application of the technology and bolstering confidence in system models and performance ratings. Dissemination of information pertaining to the economics, deployment, and operation of an HTFC/AC system represents a key component of this project. The knowledge and experience derived from this research has the potential to benefit many members of the public by furthering the understanding of HTFC/AC technology. Informing a target audience of policy makers, students, engineers, energy professionals, building owners, and investors of the details of this HTFC/AC system will serve to expand awareness and potentially increase market penetration of the technology. The success of the technology transfer aspect of this project will depend on an effective public outreach campaign grounded in a strong technical foundation established through rigorous data collection. Section 5 outlines the strategy that the Advanced Power and Energy Program (APEP) has developed in order to facilitate this goal.

5.2 TECHNOLOGY TRANSFER INTRODUCTION

New technologies are continually being developed in the energy field with the goal of increased efficiency and reduced emissions. With the breadth of studies being conducted within the distributed generation arena, it is important that policy makers, engineers, energy professionals, building owners and investors be made aware of emerging technologies in the market-ready phase. This is especially true for technologies that are first of a kind.

Through this HTFC/AC project, APEP initiated and is actively participating in the deployment of a high temperature molten carbonate fuel cell and absorption chiller system at the University of California, Irvine Medical Center. The 1.4 Megawatt (MW) fuel cell will provide electricity with low emissions and virtually zero criteria pollutants. Cooling generated by the fuel cell exhaust gas flowing through the absorption chiller increases the efficiency of the system to over 70% while offsetting the fuel or electricity normally used to produce chilled water for the Medical Center's HVAC cooling needs. The exhaust from a high temperature fuel cell has never been used in an industrial setting to directly drive an absorption chiller and provide cooling. With incentives in California such as the Self-Generation Incentive Program (SGIP), the time to bring this technology to market has never been better. Educating the critical stakeholders previously identified will enable increased market penetration of HTFC/AC systems, which are particularly well-suited to applications in California that value electricity and cooling (arid climate). Increased market penetration could lead to capital and O&M cost reductions, two of the largest inhibitors of fuel cell technologies today (Ref. Section 4.4), leading to increased use of HTFC/AC technology with corresponding GHG and criteria pollutant emissions reductions. Therefore, the transfer of knowledge gained from this project is crucial so that the public can be informed of the technology's presence in the distributed generation market place.

5.3 TECHNOLOGY TRANSFER PLAN

The HTFC/AC deployment at the University of California, Irvine Medical Center is unique in that it will not only provide full-time electricity and cooling, but will also serve as a showcase for visitors interested in the technology. The location, layout, presentation and ambiance of the system were specially designed with this in mind. The characteristics of HTFC/AC systems lend them toward areas with warmer climates which have a high demand for cooling in the form of air conditioning. For this reason the showcase was strategically placed in southern California. The Medical Center is located in California's heavily populated Orange County, directly adjacent to the I-5 freeway. There are five major airports within 40 miles of the Medical Center, providing easy access for out-of-state and international visitors.

The strategy for transferring knowledge and information about HTFC/AC technology to the public is based on a five point platform as shown in Figure 36.

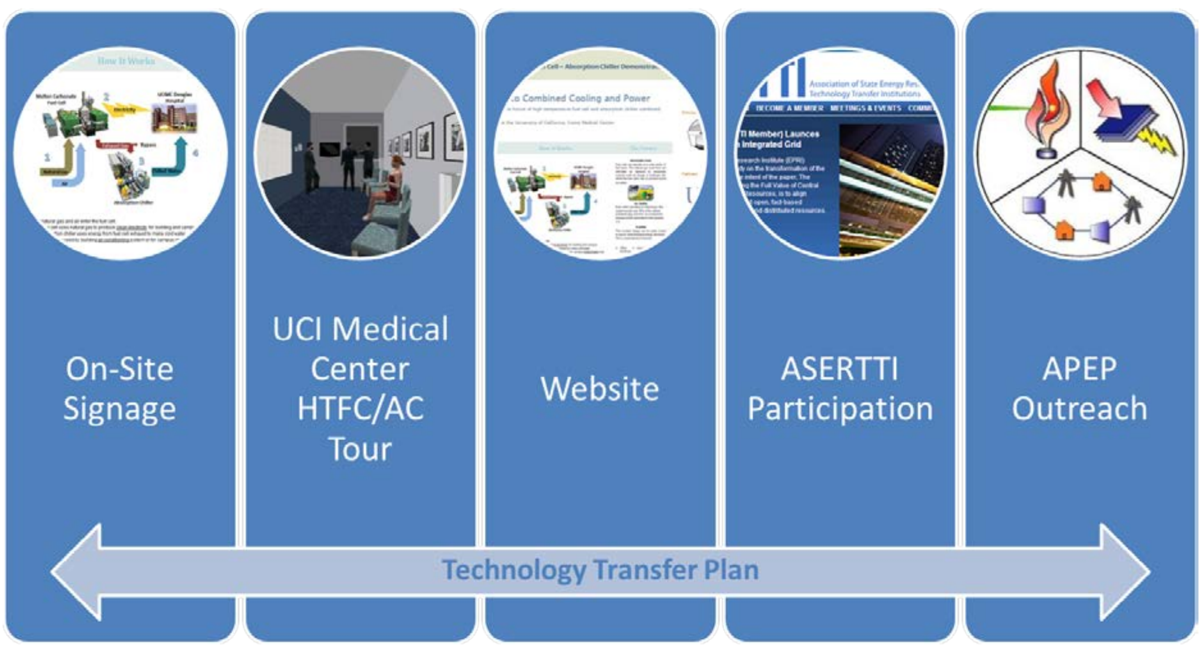

Figure 36: Technology Transfer Plan

Addressing technology transfer in five distinct ways provides a multi-facited approach to sharing information and inspiring future HTFC/AC research and investment. Each of the five approaches to technology transfer are detailed in the remaining sections of this report, with the target audiences for each displayed in Table 23.

Table 23: Target Audiences

	APEP Visitors			UCIMC Visitors		ASERTTI Users	
Technology Transfer Element	Industry	Government	Students	Facilities Mgmt. Guests	Passers-By	Industry	Research
Signage	x	x	x	x	x		
UCIMC HTFC/AC Tour	x	x	x				
Website	x	x	x	x	x	x	x
ASERTTI						x	x
APEP	x	x	x				

5.3.1 ON-SITE SIGNAGE

The purpose of the signage located on the gate around the HTFC/AC system is to enhance the educational ambiance of the installation while attracting, educating, and inspiring new visitors. The content of the billboards was chosen to create an approachable and informative display for a wide range of audiences.

The first billboard is divided into three sections; Motivation, How it Works, and The Future(Figure 37). A simplified process flow chart is included to encourage the viewer to visualize the flow of energy through the system and understand the basic purpose of each major piece of equipment. The air quality benefits and potential market sectors that HTFC/AC systems may benefit are specifically highlighted as they provide the reader with a sense of importance and promise in regards to the future of this technology. At the bottom of the billboard, the reader is encouraged to visit the project website for more information.

The second billboard has two section headings; High Temperature Fuel Cells and CCHP (Figure 38). This billboard provides more technical information and is targeted towards viewers with some Science, Technology, Engineering and Mathematics (STEM) knowledge and background. A summary of the different types of high temperature fuel cells is provided to give the reader an appreciation for the types of fuel cells that could be used in a combined cooling, heating and power application. A graphic with the advantages of high temperature fuel cells and a short section on the chemistry and electrochemistry involved gives readers a sense for what a fuel cell is, how it works, and why it is a viable option for power production. The CCHP section covers the basics of combined cooling, heating and power through the use of an absorption chiller. As absorption chillers are fairly rare, a short segment on how they work and a diagram of the process are included. The bottom of the billboard directs visitors to visit the project website or contact the National Fuel Cell Research Center if they would like more information.

The target audience for the billboards includes visitors to the Advanced Power and Energy Program (APEP) and visitors to the UCI Medical Center. APEP regularly hosts visitors from industry, government, and academia who are interested in advanced power production methods and stationary fuel cells. Any of these visitors who participate in a UCI Medical Center HTFC/AC Demonstration Tour will have the opportunity to read this signage before and after the presentation in the showcase room. It is envisioned that the Facilities Management group at the UCI Medical Center will share the HTFC/AC system with colleagues from other facilities groups. Tours held by the UCIMC Facilities Management group may include the showcase room presentation, but will primarily focus on the equipment itself along with the on-site signage.

Other billboard viewers include UCI Medical Center staff and patients who pass by the equipment. Colorful backgrounds and interesting graphics are meant to draw the attention of anyone near the equipment and encourage them to visit the site and learn more about the work being done there.

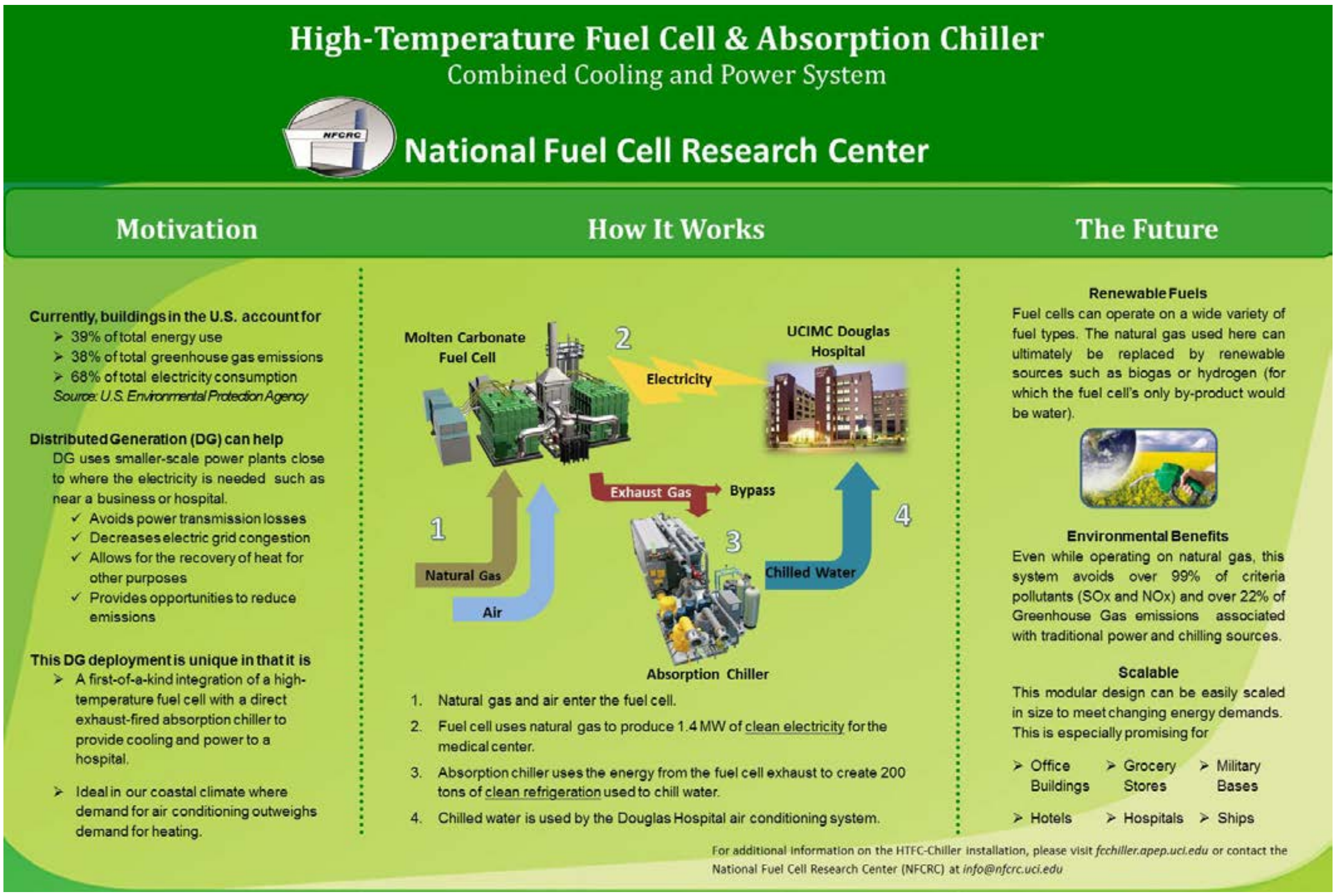

Figure 37: Billboard 1

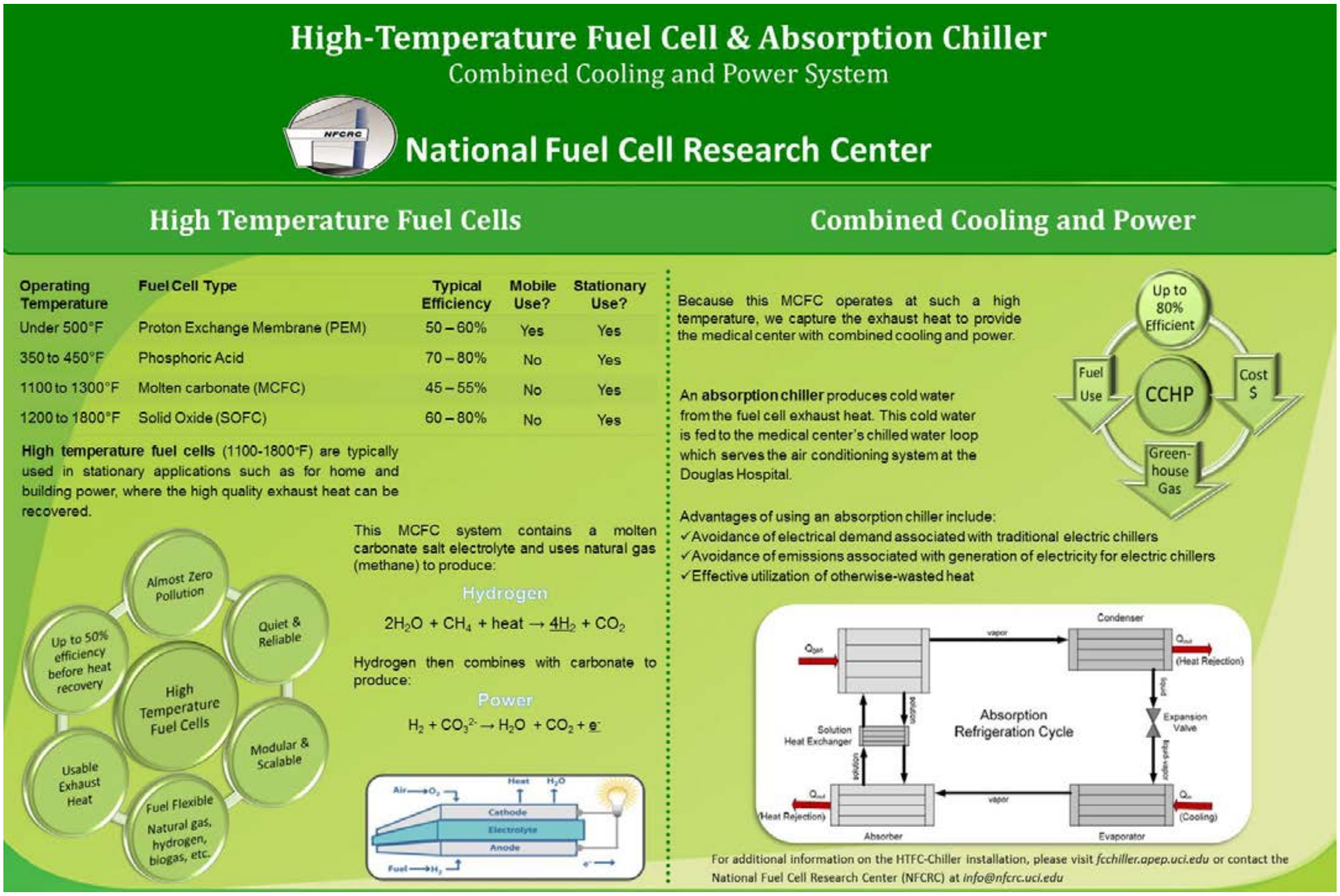

Figure 38: Billboard 2

5.3.2 UCI MEDICAL CENTER HTFC/AC TOUR

Tours of the HTFC/AC system given by APEP staff are meant to educate and inspire visitors while providing the technological background required for visitors to promote future HTFC/AC ventures and research. The highlight of the UCI Medical Center HTFC/AC Tour is the technology transfer presentation experience in the dedicated showcase room adjacent to the fuel cell system.

5.3.3 TECHNOLOGY TRANSFER ROOM

The technology transfer room is an enclosed office space directly adjacent to the HTFC/AC system in which visitors can view real-time plant data and participate in an interactive presentation about the technology led by APEP or UCI Medical Center staff. The first generation technology transfer room will be located in an eight by twenty foot portable building. The technology transfer room will relocate in 2016 to a newly constructed multi-level office building located off of the south-west corner of the HTFC/AC footprint. An office space of comparable size to the portable building will be dedicated to the showcase, and will offer a bird's-eye view of the HTFC/AC system. Figure 39 shows a preliminary layout of the site and indicates the location of both the first and second generation technology transfer rooms.

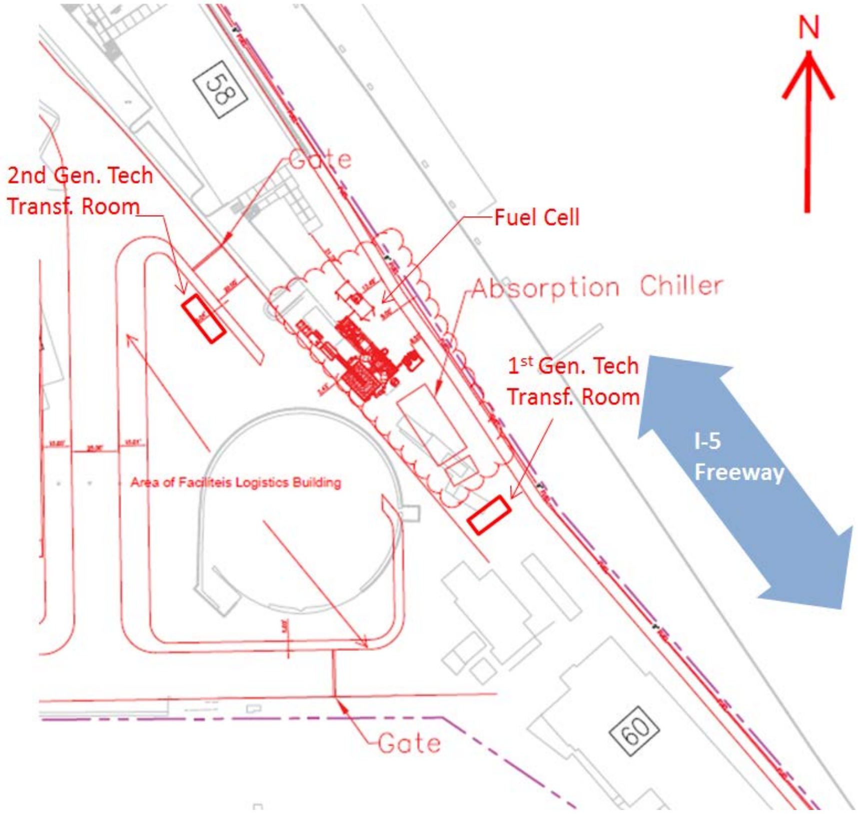

Figure 39: Technology Transfer Room Locations

The general interior layout of the first generation technology transfer room has been developed. It is envisioned that the second generation room will mimic the first with only slight variations where necessary. A floor plan for the first generation room is shown in Figure 40.

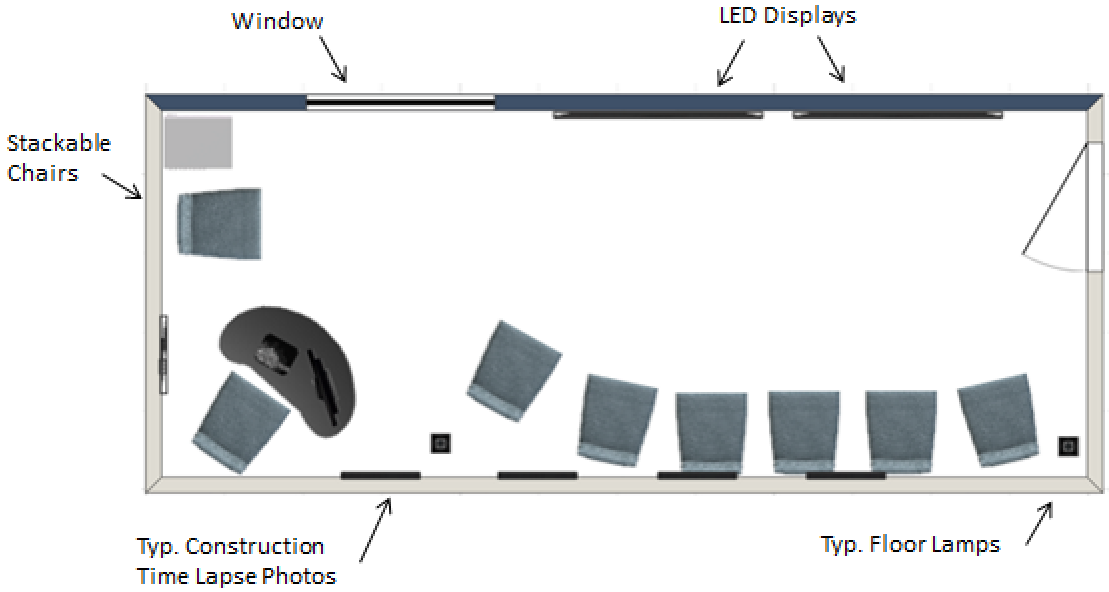

Figure 40: Technology Transfer Room Layout

A typical APEP tour group will consist of four to eight people, with the technology transfer room being able to accommodate up to ten guests and one presenter.

Figure 41: Technology Transfer Room Interior Design, Left

Figure 42: Technology Transfer Room Interior Design, Right

The technology transfer room will receive real-time plant data from the central communications board in the field via Ethernet connection to the communications room in UCIMC Building 58. Plant data will be stored on a hard drive in the technology transfer room and used to populate the graphs and schematics presented during tours. To accompany the real-time data stream, a time-lapse video of construction was shot between October 18, 2014 and February 27, 2015. The video is a compilation of still shots taken from the roof of an adjacent building every fifteen minutes between the hours of 8:00 AM and 4:00 PM. Through image processing software, the still shots are strung together into a movie which lasts just over one minute. Visitors will be able to see the HTFC/AC equipment from the window, and two LED monitors will display real-time data, the construction time-lapse footage, and other information relevant to HTFC/AC technology. A display plan is summarized in Table 24.

Table 24: Display Content

	60" LED Display 1	**60" LED Display 2**
Entrance	Construction Time-Laps	Real-Time Plant Data
Presentation	PowerPoint Presentation slides	Alternates between Real-Time Plant Data and Historical Trend Data
Egress	Construction Time-Laps	Real-Time Plant Data

5.3.4 SHOWCASE TOUR EXPERIENCE

The HTFC/AC project layout was specifically designed to provide an informative and inviting showcase experience. Tour groups visiting the site can expect a 30 - 40 minute tour by an expert in fuel cell technologies, all in an inviting and comfortable setting. A typical agenda for a tour provided by APEP is detailed below.

a. Visitors park in the dedicated Fuel Cell parking spots near the equipment.
b. Visitors walk around the perimeter of the plant, outside the decorative fence reading signage and observing the system in operation.
c. Tour guide (usually APEP staff or graduate student) answers initial questions then leads group into technology transfer room.
d. Tour guide gives a 15 – 20 minute presentation on the system.
    i. History
    ii. Novelty
    iii. How it works (with real time data displayed)
    iv. Displays trend data and highlights energy cost savings and emissions
e. Tour group leaves room and processes back toward the HTFC/AC system for a final question and answer session.

5.4 WEBSITE

A website has been established at http://fcchiller.apep.uci.edu/ to provide background information on the project, real-time data monitoring capabilities, and a 24/7 showcase environment for viewers of all around the world. The website, managed by APEP personnel, is targeted toward three groups of people.

- People who have visited the installation and want to learn more.
- People who have heard of the project and want more information.

- People who are interested in installing their own HTFC/AC system and want to learn from the operating experience derived from the UCI Medical Center installation.

A screen shot of the website's homepage is shown in Figure 43. Links to the U.S. Department of Energy CHP Technical Assistance Partnership (Pacific) website and the California Stationary Fuel Cells Collaborative website are found at the bottom of the homepage. The sections on the right of the homepage show a slide show of organization seals. Principle investigators referred to on the website include APEP, NFCRC, and FuelCell Energy. Partners referred to on the website include the California Energy Commission, UCI, and the South Coast Air Quality Management District.

Along the bottom of the website banner there is a navigation ribbon that allows users to view each of the pages within the site. Real-time plant data are available for users to watch on the second page of the site. The graphic that displays this information is shown in Figure 44. Similar figures are used to display fuel cell specific real-time data and trend data on their respective pages. Construction photos also have a page on the site. Valuable operating experience gained from the commissioning of the system, during the ASERTTI Field Protocol test, or during normal plant operation will be included on an "Operating Experience" page to help streamline future HTFC/AC installations.

The website is a valuable tool for accomplishing the technology transfer goals of this project and will be maintained and updated by APEP personnel throughout the life of the project in order to maximize its effectiveness.

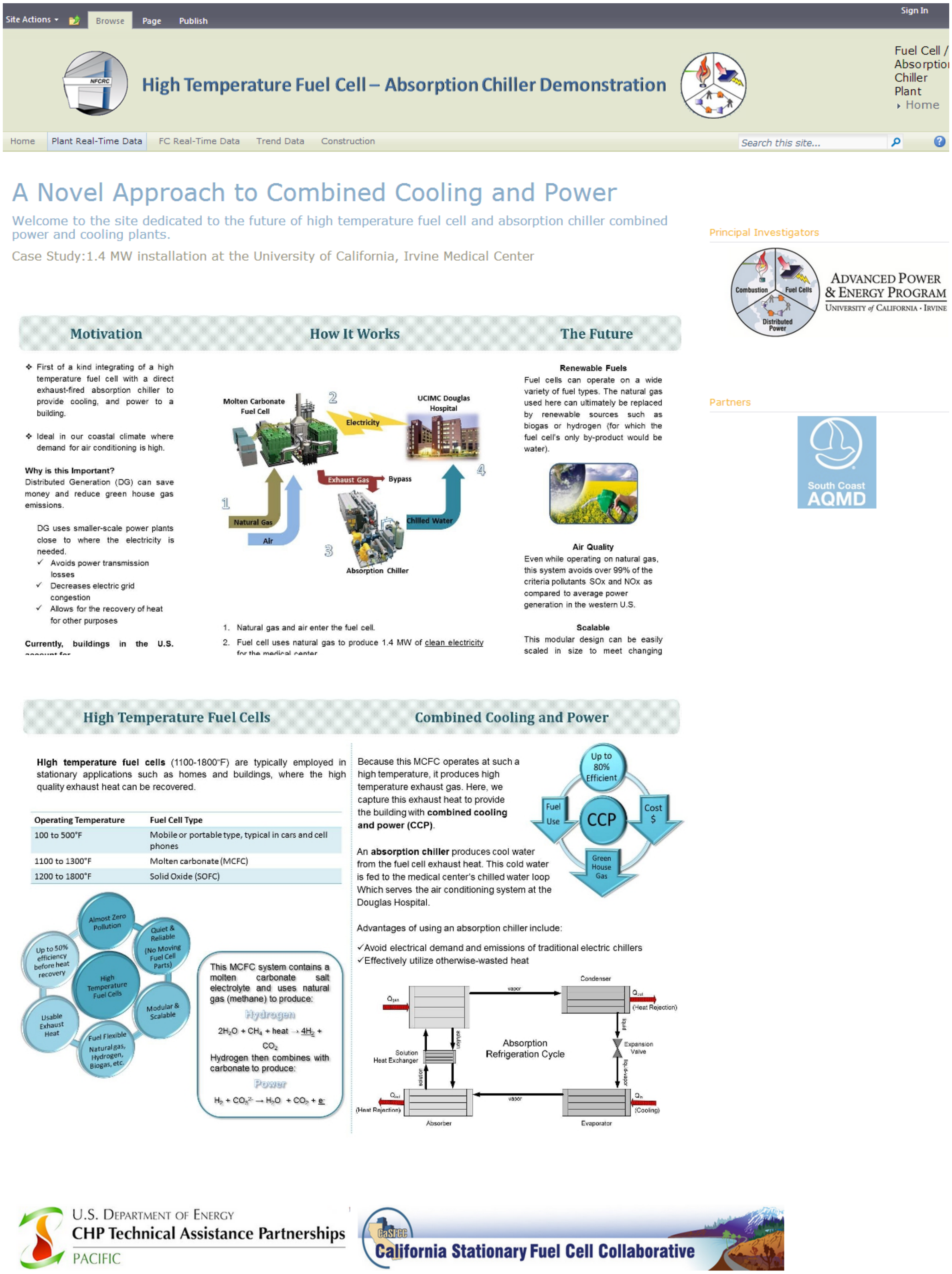

Figure 43: Website Homepage

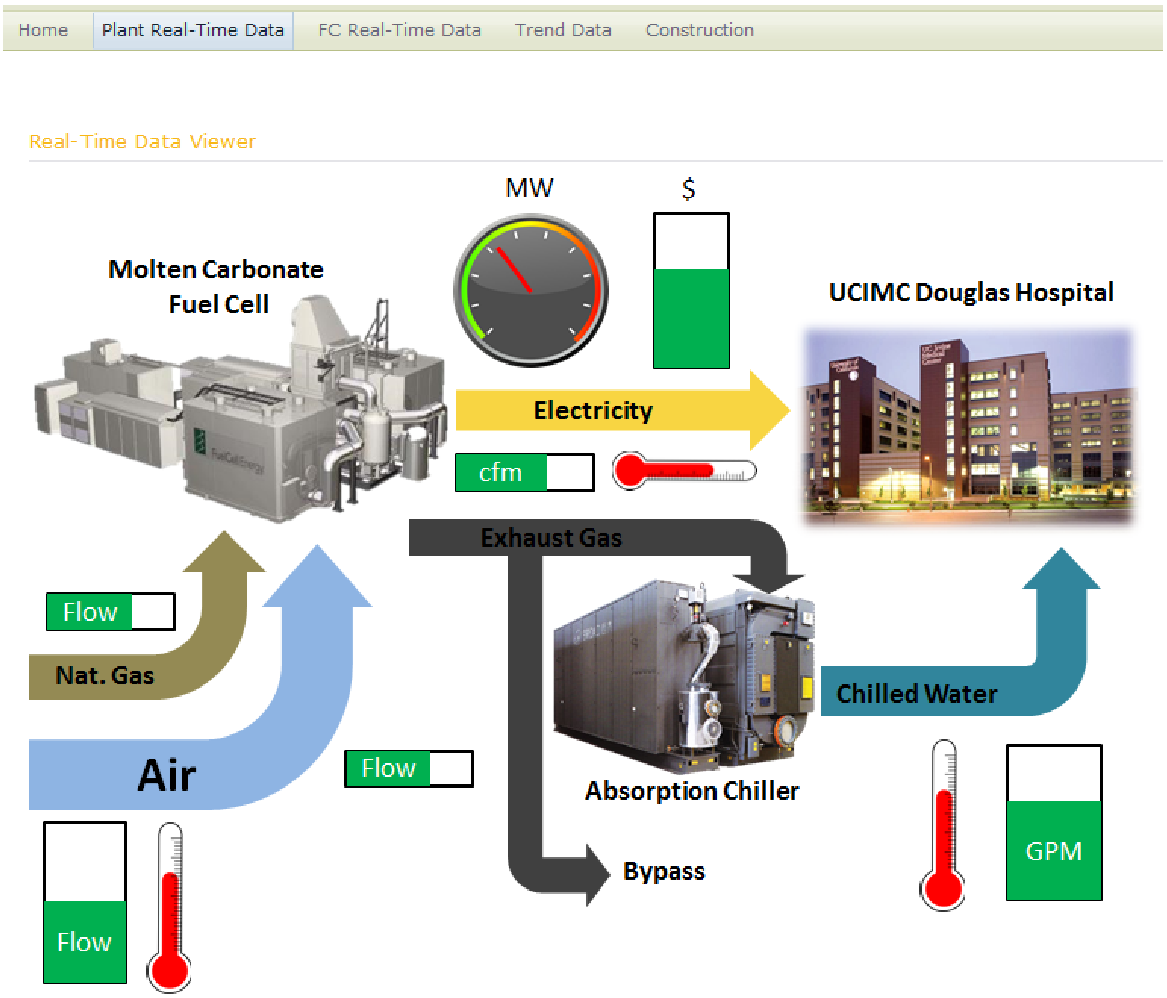

Figure 44: Plant Real-Time Data Page

5.5 ASERTTI OUTREACH

The Association of State Energy Research and Technology Transfer Institutions (ASERTTI) is a nonprofit organization whose goal is to increase the effectiveness of energy research efforts by sharing technical and operational power generation technology information among its members and associates [34]. APEP has strategically chosen ASERTTI as a platform by which to transfer operational information as the recipients of the data are in highly influential positions within the distributed generation research and development community. ASERTTI members and associates include the California Energy Commission, Brookhaven National Laboratory, Advanced Energy Corporation, Energy Industries of Ohio, Energy Center of Wisconsin, Northeast Energy Efficiency Partnership, New York State Energy Research and Development Authority, Iowa Energy Center, Louisiana Department of Natural Resources, EnergizeCT, North Carolina State University, and the University of Illinois–Chicago to name a few [34]. ASERTTI members share research findings and operating experience by sharing information on the ASERTTI website and by collaborating at ASERTTI conferences.

In order to standardize the platform on which distributed generation technologies are shared and compared, ASERTTI has published a set of testing protocols under the auspices of "ASERTTI Distributed Generation Performance Testing Protocol" [34]. APEP will use the Field Test Protocol and the Long Term Monitoring Protocol to perform the commissioning and monitoring testing for the HTFC/AC system. The results of each test protocol will be available on the ASERTTI website for other members to access, along with a link to the APEP managed HTFC/AC website.

The value of having actual operating data for a system as opposed to having only manufacturer specifications is in the assurance it provides future owners and investors that the system will operate in reality as it was design to operate on paper. This is especially true for systems such as the HTFC/AC which have never before been proven on the commercial scale. A sample of information that will be available for the HTFC/AC system through the ASERTTI website is summarized in the following sections. Including the HTFC/AC results in the ASERTTI database will promote technology transfer to key organizations in the distributed generation sector, and will help ensure the success of the overall technology transfer plan.

5.6 ADVANCED POWER AND ENERGY PROGRAM STRATEGIC ALLIANCES

The Advanced Power and Energy Program (APEP), which encompasses the National Fuel Cell Research Center and the UCI Combustion Laboratory serves as a central hub for interaction and coordination between industry, academia, and various state and federal government entities. The APEP vision of collaboration between these groups is depicted in Figure 45.

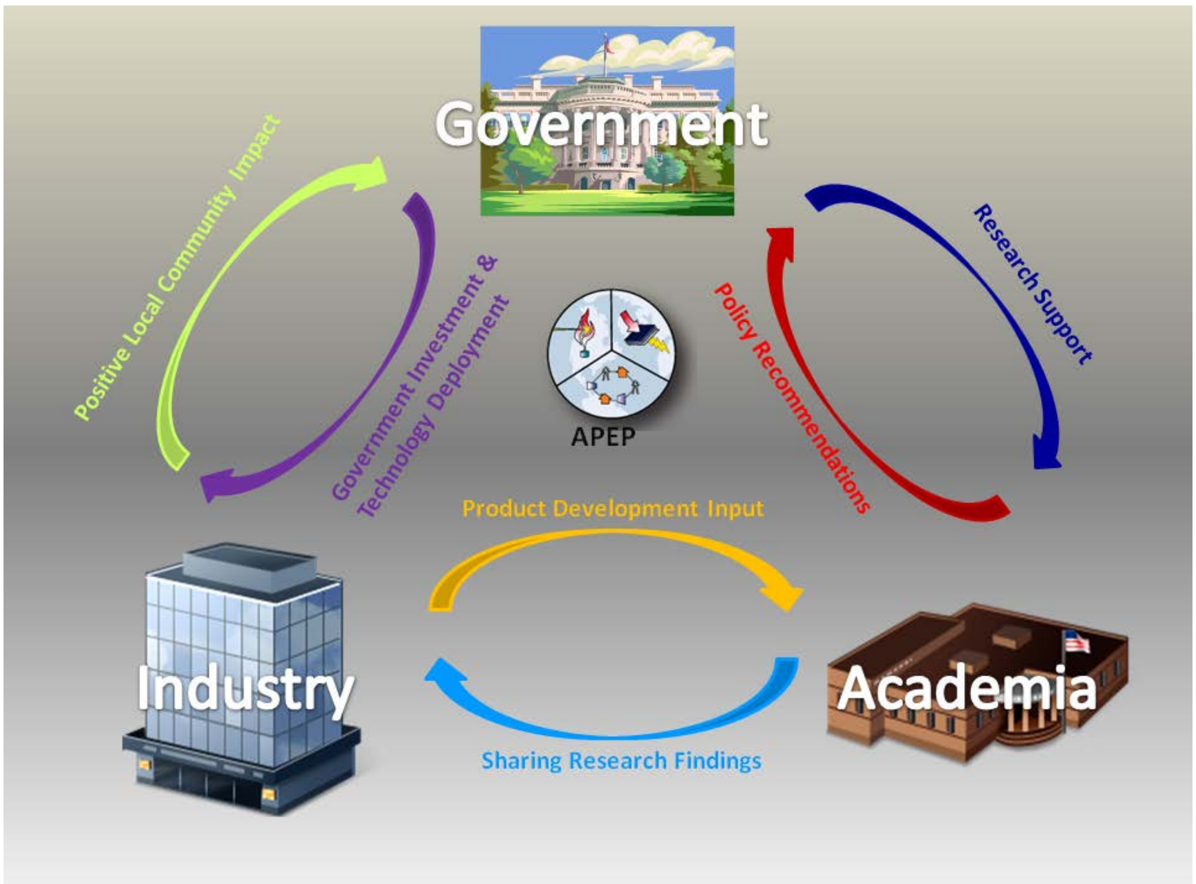

Figure 45: Industry, Government and Academia Relations

Dissemination of information and results for the HTFC/AC project will benefit from the unique position APEP holds between these groups. APEP has formed partnerships with leaders in the automotive, power generation, and aerospace industries. In doing so, synergistic relationships have formed in which the lag time between research findings and industrial applications has diminished and APEP has benefited from the marketing and product design experience that is unique to industry. Extending beyond industry, APEP partnerships include government agencies as well as other domestic and foreign academic institutions. A non-exhaustive list of APEP strategic partnerships is provided in Table 25. Results of the HTFC/AC project will receive wide exposure from APEP conference participation, technical papers, industry partnerships, government partnerships and public outreach.

Table 25: APEP Strategic Partnerships

INDUSTRY	**GOVERNMENT**	**ACADEMIA**
General Electric	NTSEL	Doshisha U.
Siemens	DOE - RAC	UC Berkeley
FuelCell Energy	DOE - CaSFCC	UC Davis
General Motors	DOD - Base Camp	Tsinghua U.
Toyota	DOE - RAC	Hamburg U.
Honda	EPA	Llieda U.
Nissan	ARB	U. of Tokyo
Hyundai/Kia	CEC	KAIST
Mercedes-Benz	CPUC	U. of Genoa
Mitsubishi	F&A	Seoul National U.
ZipCar	DGS	U. of Birmingham
Sempra	CAISO	Imperial College
PG&E	AQMD	Georgia Tech

Edison Intl.	BAAQMD	U. of Washington
Shell	SJVAPCD	CSU San Francisco
Chevron	City of Irvine	CSU San Diego
Air Products		CSU Los Angeles
Linde		
Rolls-Royce		
Solar Turbines		
Pratt & Whitney		

5.7 DATA ACQUISITION STRATEGY

In order to support the technology transfer goals of the on-site showcase environment as well as the web-based and ASERTTI based outreach platforms, quality raw data must be gathered from the demonstrative HTFC/AC system as it operates at UCIMC. The data acquisition strategy for this project is based on a comprehensive portfolio of measurements which include parameters relevant to both industry enlightenment and future research (Ref. Section 5.8). A data acquisition module written in LabVIEW® collects and stores the measurement data and makes it accessible for real-time and future use (Ref. Section 5.11).

5.8 DATA AQUISITION PORTFOLIO

The following data acquisition portfolio was compiled to serve as an input to the technology transfer aspect of the project at UCIMC. Specific attention is paid to the accessibility of each measurement point and instrumentation design is aimed at reducing cost while supporting the research and long term monitoring goals of the project.

Table 26: System Identifiers

System Identifiers	
Absorption Chiller	AC
Chilled Water System	CHW
Cooling Water System	COW
Fuel Cell System	FC
Plant	P

Table 27: Data Acquisition Portfolio

			Relevance			
Type	**Parameter**	**System**	**Market**	**Thermo Model**	**Econ Model**	**Other**
Flow						
	Exhaust Flow to Absorption Chiller	AC		x		
	Chilled Water Flow	COW		x		
	Cooling Water Makeup Flow Rate	COW		x	x	
	Cooling Water Flow Rate	COW		x		
	Water Supply to FC	FC	x		x	
	NG Flow to FC	FC	x	x	x	
	Fresh Air Inlet Flow	FC		x		
	Totalized DG Flow	FC		x		
	City Water Supply Totalized Flow	FC	x		x	
	Totalized NG Flow	P	x	x	x	
Temperature						
	HTG Temperature	AC		x		
	Generator Temperature	AC		x		
	HTG Heat Source Inlet Temperature	AC		x		
	HTG Heat Source Outlet Temperature	AC		x		
	LTG Heat Source Inlet Temperature	AC		x		

	LTG Heat Source Outlet Temperature	AC		x		
	HTG Crystallization Temperature	AC		x		
	LTHE Diluted Solution Inlet Temperature	AC		x		
	LTG Crystallization Temperature	AC		x		
	Exhaust Temperature from Absorption Chiller	AC		x		
	Chilled Water Inlet Temperature	CHW		x		
	Chilled Water Outlet Temperature	CHW		x		
	Cooling water Inlet temperature	COW		x		
	Cooling Water Outlet Temperature	COW		x		
	Exhaust Temperature (FC)	FC	x	x		
	Stacks CD Exhaust Outlet Temperature	FC		x		
	Stacks AB Exhaust Outlet Temperature	FC		x		
	Humidifier Exhaust Gas Outlet Temperature	FC		x		
	Header A Exhaust Gas Polisher Outlet Temperature	FC		x		
	Header B Exhaust Gas Polisher Outlet Temperature	FC		x		
	Water Supply Temperature to FC	FC		x		
	Fuel Inlet Temperature	FC		x		
	Fresh Air Inlet Temperature After Heater	FC		x		
	Air Heater Inlet Temperature	FC		x		
	Exhaust Temperature	FC		x		
	Fuel Superheater Temperature x4	FC		x		
	Cathode Inlet Temperature x4	FC		x		
	Mixer/Eductor to Catalytic Oxidizer Temperature x2	FC		x		
	Mixer/Eductor Temperature x2	FC		x		
	A/O Manifold Temperature x4	FC		x		
	Turn Manifold Temperature x4	FC		x		
	Catalytic Oxidizer Temperature x2	FC		x		
	Ambient Temperature	P		x		
	Control Cabinet Temperature	P				x
Pressure						
	N2 Supply Pressure	FC				x
	Fresh Air Inlet Pressure	FC		x		
	N2 Pressure	FC		x		
	Cathode Inlet Pressure	FC		x		
	Cathode Inlet Differential Pressure x3	FC		x		
Current						
	BOP Current from EPM (Scaled)	FC	x			

	Fuel Cell DC Current (PCU)	FC	x	x		
	TB Line A Current Line A, B and C	FC				x
Voltage						
	BOP Voltage from EPM (Scaled)	FC	x			
	Stack AB Fuel Cell Voltage	FC	x	x		
	Stack CD Fuel Cell Voltage	FC	x	x		
	TB Volts Phase AB	FC	x			
	TB Volts Phase BC	FC	x			
	TB Volts Phase CA	FC	x			
	End Cell Voltage x 4	FC		x		
Power						
	Chilled Water Pump Power	CHW			x	
	Cooling Tower Fan Power	COW			x	
	Cooling Water Pump Power	COW			x	
	PCS KW Output KW Leader Master Real	FC				x
	PCS KW Output KW Leader Slave Real	FC				x
	TB 3 Phase kilovars	FC	x			
	TB 3 Phase kilowatts	FC	x			
	De-rated Total Maximum Power (KW*10) (Integer)	FC	x			
	Corrected TB KW to Customer	FC	x			
Frequency						
	Solution Pump frequency	AC				x
	Refrigerant Pump frequency	AC				x
	Cooling Water Pump frequency	COW				x
	Cooling Tower Fan Frequency	COW				x
Indications						
	Cooling Mode	AC				x
	Heating Mode	AC				x
	Hot water Mode	AC				x
	Switch-on Mode	AC				x
	Dilution Off Mode	AC				x
	Switch-off Mode	AC				x
	Fault Stop Signal	AC				x
	Fault Alarming Signal	AC				x
	HTG Solution Level Zone	AC				x
	Refrigerant Level Zone	AC				x
	Solution Pump Running	AC				x
	Refrigerant Pump Running	AC				x
	Absorber Pump Running	AC				x
	Vent Pump Running	AC				x

	Heating Water Pump #1 Running	AC				x
	Heating Water Pump #2 Running	AC				x
	Hot Water Pump #1 Running	AC				x
	Hot Water Pump #2 Running	AC				x
	HTG Heat Source Valve Opening	AC				x
	LTG Heat Source Valve Opening	AC				x
	Chilled Water Pump #1 Running	CHW				x
	Chilled Water Pump #2 Running	CHW				x
	#1 Chilled Water Flow Switch	CHW				x
	#2 Chilled Water Flow Switch	CHW				x
	Cooling Water By-pass Valve Opening	COW				x
	Cooling Water Pump #1 Running	COW				x
	Cooling Water Pump #2 Running	COW				x
	Cooling Fan #1 Running	COW				x
	Cooling Water Flow Switch	COW				x
	FC Alarms to Customer	FC	x			x
Other						
	Highest LEL % from all Skids (Water Treatment)	FC				x
	N2 Storage Tank Level	FC				x
	Measured Fuel Utilization	FC	x	x	x	
	TB Power Factor	FC	x			
	BOP Power from EPM (Scaled)	FC	x			
	PCU Efficiency Setpoint	FC	x			
	Module A Operation Hours in Tenths	FC	x		x	
	Trip Index to Customer	FC				x
	Ambient Air Monitor	P	x		x	
	Effluent Air Monitor	P	x		x	

5.9 KEY DATA POINTS for THERMODYNAMIC ANALYSES

There are two components to the Advanced Power and Energy Program's HTFC/AC thermodynamic model; the fuel cell and the absorption chiller, with the output of the fuel cell model serving as the input to the absorption chiller model. The high temperature molten carbonate fuel cell (MCFC) model is written in Matlab Simulink® and includes chemical, electrochemical, and thermodynamic equations that govern any MCFC configuration. Data taken from the UCIMC demonstration will be used to tune the model to more closely represent FuelCell Energy's line of DFC fuel cells. Specific measurements were selected which will guide the estimation of many of the model initial conditions and parameters. For example, the fresh air inlet flow and natural gas flow will be monitored and compared to the values estimated in the model. Also, exhaust gas temperature coming from the individual stacks, and the final exiting exhaust gas temperature will be measured and compared to their calculated values. The fuel cell electrical output will also be measured and compared to calculated values. Knowing what the value for these key thermodynamic process points should be will help guide future model improvement and verification.

The Advanced Power and Energy Program's absorption chiller model is written in Aspen® and takes the exhaust flow conditions from the fuel cell model as its initial inputs. It then uses a series of heat exchanger and flow processing calculations to simulate the operation of a 40 refrigeration ton absorption chiller. Certain measurements being taken from the UCIMC demonstration will be key in scaling the model up to 200 refrigeration tons and making its output closely match the output of the BROAD U.S.A model chiller used for this demonstration. These measurements include the temperature of process fluid in both the high and low temperature generators as well as the heat exchanger inlet temperature and the temperature of the exhaust gas leaving the absorption chiller. The actual chilling produced from the machine by will be calculated using the chilled water flow rate and temperature change. The amount cooling provided by the cooling tower will also be monitored. Each of these inputs will effect assumptions made in the model and can be used to tune the model to better reflect reality.

5.10 KEY ECONOMIC MODEL DATA POINTS

The HTFC/AC economic model described in Section 4 of this thesis relies on electricity, cooling, and heating energy flows to characterize the operation of the HTFC/AC system. The energy flows are calculated in the technical code based upon specified building demand and equipment capacities. The inputs used for calculating the equipment capacities were assumed based upon manufacturer specifications and best available industry knowledge. The deployment of an actual HTFC/AC system at the UC Irvine Medical Center offers a unique opportunity to enhance the economic model by replacing many of the assumed operational values with measured inputs.

The G-Matrix is an excel file which serves as the primary input for the baseline economic and technical parameters used in the economic model. Figure 46 is a sample G-Matrix. The far left column lists all of the input parameters and the equipment types are listed along the second row. The entire array of equipment types is not shown, but includes the following: 300 kW, 1.4 MW, or 2.8 MW fuel cell, 40, 200 or 400 ton absorption chiller, electric chiller, thermal energy storage tank, heat recovery unit, and natural gas boiler. Electricity imports or exports are also treated as a “piece of equipment” in the economic model. For each piece of equipment, assumptions were made pertaining to the twenty four different input categories.

	Input Category	Technology # / Input Units	(11) Electricity Imports	(1) Fuel Cell	(2) Fuel Cell	(3) Fuel Cell
1	Gross Capacity	MW	0.5	0.3	1.4	2.8
2	Annual Cap Factor (Primary Product)	Decimal, 0-1	0.65	0.9	0.9	0.9
3	Instant Cost (Overnight Construction)	$/kW	0	3600	3300	3000
4	FOM	$/kW-yr	0	200	200	200
5	VOM	$/MWh	0	0.21	0.21	0.21
6	Initial Heat Rate	MMBtu/MWh-e	0	8.06	8.06	8.06
7	Annual Heat Rate Degradation	Decimal, 0-1	0	0.009	0.009	0.009
8	Annual Capacity Degradation	Decimal, 0-1	0	0.009	0.009	0.009
9	Debt Term	Years	0	20	20	20
10	Economic Life	Years	20	20	20	20
11	Federal Tax Life	Years	0	10	10	10
12	State Tax Life	Years	0	20	20	20
13	Ad Valorem Tax Rate	Decimal	0	0.01098	0.01098	0.011
14	Annual Starts	#/yr, if any	0	4	4	4
15	Start-Up Fuel per Start	MMBtu/MWh	0	10	10	10
16	Stack Life (Fuel Cell Only)	Years	0	5	5	5
17	Master Matrix: Primary Product Column	Integer, 1-9	1	6	6	6
18	Fuel Type (0 = Waste Heat, Renewable, or TES; 1 = Natural Gas; 2 = Electricity)	Fuel Type	2	1	1	1
19	Year 1 Transmission Cost	$/MWh	4	0	0	0
20	CO2 Emissions Factor	tons CO2/MWh (or MMBtu)	0.318	0.0645	0.0645	0.0645
21	Renewable Resource Percent	Range = 1-100	19.8	0	0	0
22	Ownership (1=Merchant, 2=POU, 3 = IOU)	Ownership Code	2	1	1	1
23	Equipment Type	Integer, 1-7	7	1	1	1
24	COP		0	0	0	0
1	Percent of Construction in Year 1		1	0.85	0.85	0.85
2	Percent of Construction in Year 2		0	0.15	0.15	0.15
3	Percent of Construction in Year 3		0	0	0	0
1	Months of Construction in Year 1		0.0001	12	12	12
2	Months of Construction in Year 2		0	9	9	9
3	Months of Construction in Year 3		0	0	0	0

Figure 46: Sample G-Matrix

Many of the inputs will be manually monitored and recorded as they do not require electronic metering. For example, maintenance records will track the number of annual starts of the fuel cell system. But many parameters in the G-Matrix and in the Matlab economics code which do require electronic monitoring are included in the data acquisition portfolio. Among the most important measurements are the water consumption, totalized natural gas flow, parasitic load fraction and overall efficiency. Monitoring these key parameters and recording economic characteristics of the installation at the UC Irvine Medical Center will allow for the G-Matrix to be updated and the economics model to better represent real world applications.

5.11 DATA ACQUISITION STRUCTURE

A data acquisition module was created using LabVIEW Version 11.0.1, 2011 by National Instruments. The module collects, organizes, and stores data from the main communications panel in the plant. It allows for real time and historical visualization of the plant operation based on the measurements being taken. The data acquisition module consists of two main LabVIEW® programs; one entitled UCIMC_Data_Acquisition.vi (DAQ) which handles data acquisition from main communication board, real time visualization, and data logging, and one entitled UCIMC_Historical_Data.vi which handles historical data recall and graphing.

The main communication board transmits data from both the FuelCell Energy “Red Lion PLC” and the Self Generation Incentive Program (SGIP) reporting panel to the communications room in Building 58 at UCIMC. The DAQ module function pulls in data from the UCIMC Building 58 communications room using a Modbus/TCP connection to the on a desired sample rate interval. Because most of the data points coming in from the Red Lion PLC are 32 bit floats, they are split into two 16 bit units for transmission to match the 16 bit Modbus protocol registers. Once the 16 bit units reach the LabVIEW® DAQ program, they are recombined into 32 bit floats.

This DAQ module holds up to 24 hours' worth of data in RAM on the server, then transfers a batch of data to an external hard drive at 11:59 PM each night. The purpose of collecting a batch of data before writing to a file is to decrease wear on the hard drive by minimizing the amount of calls made to it. The Modbus communications are handled by a National Instruments published Modbus driver, and the sample frequency and IP address of the PLC are easily edited during runtime, even when the program has been exported as an execution file.

The Historical Data module recalls a list of all dates that data were saved on. Then, it selects data based on what timescale the user specifies, and only recalls data for those given dates. Next, it evenly reduces data arrays down to a reasonable resolution for graphing. Although much of the logic behind data selection and graphing were manually coded, this portion of program has been thoroughly tested and works smoothly with dummy data sets. The screenshots below demonstrate the Historical Data module operating properly with a set of test data. Figure 1: shows program properly handling errors when no data are available, and Figure 2 shows the program recalling and graphing the test data from a given time period.

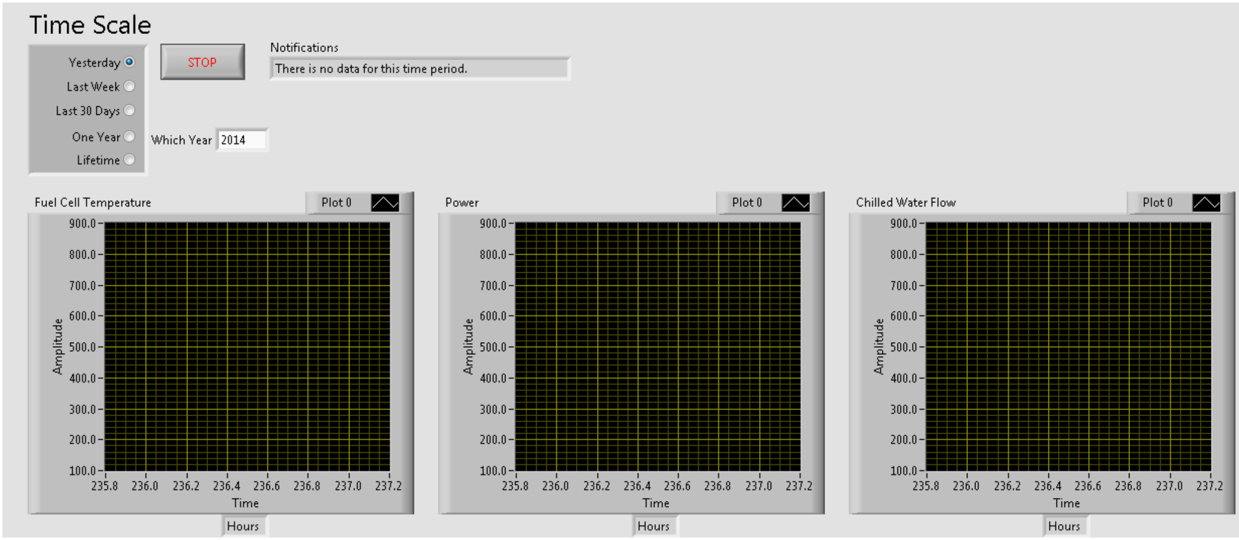

Figure 47: Attempt to Recall Non-Existing Data

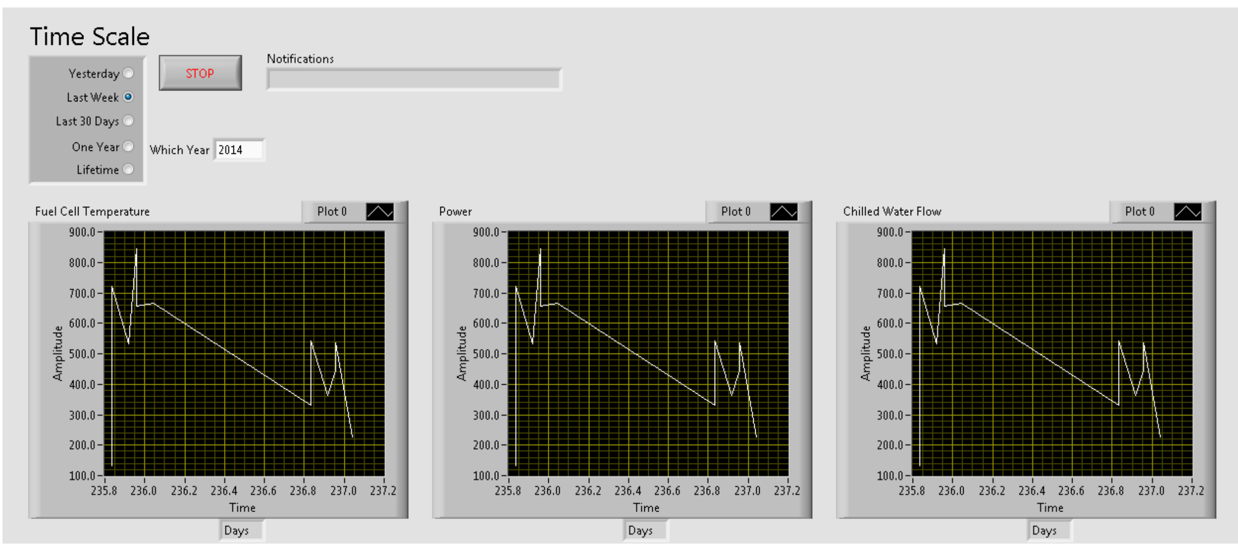

Figure 48: Recalling Data from a Given Time Period

5.12 NEXT STEPS FOR DATA ACQUISITION

The installation at UCIMC is not complete at the time of this thesis, and the program cannot be implemented in the field. The program will be ready to be installed once the communications network is in place at UCIMC and the office trailer is equipped with a computer and an external hard drive. It is important that the final data set coming from the Red Lion PLC and the SGIP reporting panel be aligned with the DAQ program, and that data be available from at least one channel in order to begin commissioning the program. Though both the DAQ and historical data modules have been tested in the lab, they will surely require some small modifications in order to handle real-time data from the HTFC/AC installation. Commissioning the data acquisition system will require addressing any issues that come up while executing the following steps:

1. Set up the server computer in the APEP trailer; connect it to the UCIMC network and the external hard drive.
2. Create a "UCIMC_Data" folder on the external hard drive, change the path names in the program to point to that folder.
3. Make a "names.csv" file within that folder and fill it with a comma separated list of data point names in the order that they are transmitted in. Add year, day, hour, minute, and second to the front of the list.
4. Update the order and addresses of the data points found in the bottom section of the Data Acquisition Module's code according to the final list of Modbus Addresses sent by the operator of the Red Lion PLC and the SGIP reporting panel.
5. Export both the DAQ and Historical Data VI's to .exe files, and be sure to select the option to package all necessary sub-VI's in the .exe file.

6. Move the .exe files to the server and adjust the IP address of the PLC (which can be found on the third tab of the Data Acquisition module). Then, run the Data Acquisition module constantly. Run the Historical Data module when creating historical graphs.
7. Use the integrated Web Publishing Tool in LabView® to publish plots nightly to the dedicated project website.

6 CONCLUSIONS

- High Temperature Fuel Cell and Absorption Chiller (HTFC/AC) systems that are properly sized for the building they serve are both economically and environmentally preferable to traditional grid-based building utilities in southern California.

The HTFC/AC Economic Model was used to simulate various scenarios and test the economic impacts of different fuel cell and absorption chiller configurations in completion of the requirements of Task 1 of this thesis. It was found that if a HTFC/AC system in southern California is properly sized for the building (i.e., the electric and thermal products of the HTFC/AC system are fully utilized) it is economically and environmentally beneficial for the building owner to install such a distributed generation system. If the fuel cell is oversized and exporting electricity to the grid, or if the thermal output of the system is underutilized, or the financial conditions differ greatly from those assumed in this report (ref. Section 4.1.1), then the economic viability of the HTFC/AC system requires a closer look.

Ownership type, equipment capacity factors, and fuel cell installation and O&M costs are highly influential parameters in determining the economic viability of HTFC/AC systems. However, as long as the HTFC/AC system is properly sized for the loads it serves (i.e., the thermal and electric products are fully utilized), the physical and financial attributes of the system are typical, and the grid electricity rates are relatively high, HTFC/AC systems are preferable to traditional grid-based utilities. Buildings with somewhat consistent 24/7 electric and thermal loads (e.g. hospitals) are especially well suited for the early market as high temperature fuel cells which are commercially available today are designed to provide base load electricity. It is important to note that HTFC/AC technology is economically competitive with traditional grid-based utilities, but it is not necessarily the most economical choice among distributed generation technologies. Turbine generators, for instance, are far less costly to construct and deploy. However, while HTFC/AC systems may not be the most cost effective distributed generation solutions to install, they afford many unique advantages to the owner which traditional combustion-based technologies do not. These advantages include lower Greenhouse Gas and particulate emissions, less dependence on natural gas price due to increased efficiency, and less noise pollution.

- The HTFC/AC demonstration at the University of California, Irvine Medical Center (UCIMC) will advance the market penetration of HTFC/AC systems by increasing awareness and confidence in the technology throughout the distributed generation market.

The installation at UCIMC is designed to enable the distributed generation market of HTFC/AC technology by demonstrating a real-world application of the technology and bolstering confidence in system models and performance ratings. The technology transfer environment designed for the UCIMC site will maximize knowledge transfer to students, educators, key decision makers, developers and other influential members of the public using a dedicated showcase room and project website. The installation scheme is designed to present system technology and operating information in an attractive and informative manner suitable for public consumption.

The data presented through the technology transfer tools are based on real-time measurements collected from the system using the data acquisition module developed as part of this thesis. The data collected will also serve as key inputs to the HTFC/AC technical and economic models developed by the Advanced Power and Energy Program. Industry confidence in HTFC/AC performance will be enhanced by the circulation of actual operating parameters and results from verified models.

7 REFERENCES

1. IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
2. Code of Federal Regulations, Title 40, Chapter I, Subchapter C, Part 98, Subpart A, Appendix, Table A-1, Global Warming Potentials. http://www.ecfr.gov/cgi-bin/text-idx?SID=a61c01bf8ef85fe7691072cfd8cc0de8&node=ap40.21.98_19.1&rgn=div9

3. Code of Federal Regulations, Title 17, 95102, Definitions. https://govt.westlaw.com/calregs/Document/I0058E1109A3011E4A28EDDF568E2F8A2?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)

4. IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

5. IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

6. The Potential Benefits of Distributed Generation and Rate-Related Issues That May Impede Their Expansion, U.S. Department of Energy, February 2007, Page 1-7.

7. S. M. Kaplan, "Electric Power Transmission: Background and Policy Issues," Congressional Research Service, 9:14, 2009.

8. Climate Change Scoping Plan, California Air Resources Board, Page 117, 2008.

9. Timeline of California's Renewables Portfolio Standard, http://www.energy.ca.gov/renewables/index.html, updated April 10, 2013.

10. Tracking progress, Renewable Energy - Overview http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf, updated October 22, 1013.

11. California Renewable Energy Overview and Programs, http://www.energy.ca.gov/renewables/, updated April 10, 2013.

12. California Energy Almanac, Total Electricity System Power, 2013. http://energyalmanac.ca.gov/electricity/total_system_power.html

13. US Environmental Protection Agency, Clean Energy, Natural Gas. http://www.epa.gov/cleanenergy/energy-and-you/affect/natural-gas.html#footnotes

14. Emissions & Generation Resource Integrated Database (eGRID), Ninth edition with 2010 data (Version 1.0) Released 02/24/2014.

15. Externalities and Energy Policy: The Life Cycle Analysis Approach, Nuclear Energy Agency, Organization for Economic Co-Operation and Development. Figure 1: Total Life Cycle Emissions. 2001

16. US Environmental Protection Agency, Clean Energy, Nuclear Power. http://www.epa.gov/cleanenergy/energy-and-you/affect/nuclear.html

17. FuelCell Energy DFC1500 Specifications Sheet, 2013.

18. BROAD U.S.A. Specification Sheet for BZHE Chiller, Project Name; UC Irvine, 03/14/2014.

19. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office, "State of the States: Fuel Cells in America 2013", 4th Edition.

20. Vision for Clean Air: A Framework for Air Quality and Climate Planning, Public Review Draft, California Air Resources Board. June 27, 2012.

21. R. P. O'Hayre, S. W. Cha, W. Colella, F. B. Priz, Fuel Cell Fundamentals, Page 244, 2006.

22. California Commercial End-use Survey. http://capabilities.itron.com/CeusWeb

23. R. P. O'Hayre, S. W. Cha, W. Colella, F. B. Priz, Fuel Cell Fundamentals, Page 52, 2006.

24. Absorption Chillers, Southern California Gas Company, New Buildings Institute, Advanced Design Guideline Series. 1998. http://web.stanford.edu/group/narratives/classes/08-09/CEE215/ReferenceLibrary/Chillers/AbsorptionChillerGuideline.pdf

25. Thermax Sustainable Solutions, Triple Effect Chiller Product Information. 2014. http://www.thermaxindia.com/Absorption-Cooling/Products/Vapour-Absorption-Machines/Triple-Effect-Chiller.aspx

26. BGC Carbon Market Daily, BGC Environmental Brokerage Services website January 22, 2015. http://www.bgcebs.com/Register/?page=http://www.bgcebs.com/myBGC-EBS/dailys/&id=37951

27. K. S. Hosford, "Design and economic potential of an integrated high-temperature fuel cell and absorption chiller combined cooling, heating, and power system," Master's thesis, University of California, Irvine, 2013.

28. S. M. Martz, "Modeling and integration of a combined cooling, heating and power system with a high temperature fuel cell and absorption chiller," Master's thesis, University of California, Irvine, 2011.

29. FuelCell Energy website, Why Fuel Cells http://www.fuelcellenergy.com/why-fuelcell-energy/why-fuel-cells/

30. Gas Price Information for Commercial and Industrial Rates, January 22, 2015. http://www.socalgas.com/for-your-business/prices/

31. Email correspondence, Nato Flores, P.E. Consultant at University of California, Irvine Medical Center dated January 22, 2015. https://www.sce.com/wps/portal/home/regulatory/tariff-books/rates-pricing-choices/net-surplus-compensation/!ut/p/b0/04_Sj9CPykssy0xPLMnMz0vMAfGjzOINLdwdPTyDDTwtfAKNDTydnDz9zdxMjA28jfQLsh0VAY010s4!/

32. Southern California Edison Net Surplus Compensation Rate, NSCR Energy Prices, March 2015.

33. H. Ghezel-Ayagh, J. McInerney, R. Venkataraman, M. Farooque, R. Sanderson, FuelCell Energy, Inc., “Development of Direct Carbon Fuel Cell Systems for Achieving Ultrahigh Efficiency”, February 22, 2011.

34. Association of State Energy Research and Technology Transfer Institutions website, 2014. www.asertti.org

35. Association of State Energy Research and Technology Transfer Institutions, prepared by Southern Research Institute, “Distributed Generation and Combined Heat and Power Field Testing Protocol,” July 3, 2008.

36. Association of State Energy Research and Technology Transfer Institutions, prepared by Connected Energy Corp., “Distributed Generation Combined Heat and Power Long Term Monitoring Protocol,” March 4, 2008.

Appendix A

Section 4 Model Runs

Portfolio	Building	LCOE ($/MWh)	CO2 (tons)	H2O (gal)	Imported Elec (MWh)	
0 0 0 0 0 0 1 1 0 0 1	MSTB	133.4639	10386.72622	0	15540.66449	Competing Scenario
1 0 0 1 0 0 0 0 0 0 1	MSTB	123.0383	25770.58422	4978644	-31826.84801	
1 0 0 1 0 0 0 0 0 1 1	MSTB	121.0363	25770.58422	4978644	-31826.84801	
1 0 0 1 0 0 1 0 0 1 1	MSTB	119.4288	27509.65596	4978644	-31826.84801	
0 1 0 0 1 0 0 0 0 1 1	MSTB	111.2588	120262.7263	23233671	-198850.848	
0 1 0 0 1 0 1 0 0 1 1	MSTB	111.3642	120788.4041	23233671	-198850.848	
0 0 1 0 0 1 0 0 0 1 1	MSTB	105.7847	240525.4527	46467341	-411426.848	
0 0 1 0 0 1 1 1 0 1 1	MSTB	106.8682	240580.4661	46467341	-411426.848	100% Backup NGB/EC
1 0 0 1 0 0 1 0 0 1 1	MSTB	139.6737	27509.65596	4978644	-31826.84801	Zero Return on Exports
0 1 0 0 1 0 1 0 0 1 1	MSTB	141.821	120788.4041	23233671	-198850.848	Zero Return on Exports
0 0 1 0 0 1 0 0 0 1 1	MSTB	137.8523	240525.4527	46467341	-411426.848	Zero Return on Exports
1 0 0 1 0 0 1 0 0 1 1	MSTB	132.9254	27509.65596	4978644	-31826.84801	$10/MWh Return on Exports
0 1 0 0 1 0 1 0 0 1 1	MSTB	133.6992	120788.4041	23233671	-198850.848	$8/MWh Return on Exports
0 0 1 0 0 1 0 0 0 1 1	MSTB	133.5766	240525.4527	46467341	-411426.848	$4/MWh Return on Exports
1 0 0 1 0 0 1 0 0 1 1	MSTB	108.4954	1739.071742	4978644	-31826.84801	Zero Fuel Cell CO2 Taxes
0 0 0 0 0 0 1 1 0 0 1	LBVA	102.9269	514555.5775	0	733199.3804	Competing Scenario
1 0 0 1 0 0 1 1 0 1 1	LBVA	101.093	483666.7441	4978644	572641.8537	
0 1 0 0 1 0 1 1 0 1 1	LBVA	100.2666	468931.9177	23233671	387868.7012	
0 0 1 0 0 1 1 1 0 1 1	LBVA	97.52688	450318.7242	46467341	152948.0512	
0 0 1 0 0 1 1 1 0 1 1	LBVA	93.09556	209793.2715	46467341	152948.0512	Zero Fuel Cell CO2 Taxes
0 0 1 0 0 1 1 1 1 1 1	LBVA	98.05139	450219.9192	46467341	152773.9455	500 ton-hr TES
0 0 1 0 0 1 1 1 0 1 1	LBVA	97.52688	450318.7242	46467341	152948.0512	Zero Return on Exports
0 0 0 0 0 0 1 1 0 0 1	SCAQMD	85.52335	51696.90829	0	54721.11304	Competing Scenario

1 0 0 1 0 0 1 1 0 1 1	SCAQMD	85.29861	52018.2851	4978644	-6915.286027	
0 1 0 0 1 0 1 0 0 1 1	SCAQMD	95.49509	139791.5007	23233671	-181357.0342	
0 0 1 0 0 1 1 0 0 1 1	SCAQMD	95.89119	252534.5068	46467341	-393933.0342	
1 0 0 1 0 0 1 1 0 1 1	SCAQMD	81.28843	26247.70089	4978644	-6915.286027	Zero Fuel Cell CO2 Taxes
0 1 0 0 1 0 1 0 0 1 1	SCAQMD	85.48964	139791.5007	23233671	-181357.0342	Zero Fuel Cell CO2 Taxes
0 1 0 0 1 0 1 0 0 1 1	SCAQMD	86.79422	19528.77432	23233671	-181357.0342	Zero Fuel Cell CO2 Taxes
1 0 0 1 0 0 1 1 0 1 1	SCAQMD	86.912	52018.2851	4978644	-6915.286027	Zero Return on Exports
0 0 0 0 0 0 1 1 0 0 1	Test 300	114.76	32107.51	0	53826.39	Competing Scenario
1 0 0 1 0 0 0 0 0 1 1	Test 300	112.28	25770.58	4978644	-4770.39	
0 1 0 0 1 0 0 0 0 1 1	Test 300	110.79	120262.73	23233671	-171794.39	
0 0 1 0 0 1 0 0 0 1 1	Test 300	106.01	240525.45	46467341	-384370.39	
1 0 0 1 0 0 0 0 0 1 1	Test 300	114.5396	25770.58422	4978644	-4770.386824	Zero Return on Exports
0 1 0 0 1 0 0 0 0 1 1	Test 300	135.1103	120262.7263	23233671	-171794.3868	Zero Return on Exports
0 0 1 0 0 1 0 0 0 1 1	Test 300	134.7599	240525.4527	46467341	-384370.3868	Zero Return on Exports
0 0 0 0 0 0 1 1 0 0 1	Test 1400	112.44	151068.88	0	253363.93	Competing Scenario
1 0 0 1 0 0 1 1 0 1 1	Test 1400	109.74	128645.3	4978644	167955.88	
0 1 0 0 1 0 0 0 0 1 1	Test 1400	107.72	120262.73	23233671	-24435.93	
0 0 1 0 0 1 0 0 0 1 1	Test 1400	105	240525.45	46467341	-237011.93	
1 0 0 1 0 0 1 1 0 1 1	Test 1400	109.7444	128645.3008	4978644	167955.8754	Zero Return on Exports
0 1 0 0 1 0 0 0 0 1 1	Test 1400	110.154	120262.7263	23233671	-24435.93412	Zero Return on Exports
0 0 1 0 0 1 0 0 0 1 1	Test 1400	119.488	240525.4527	46467341	-237011.9341	Zero Return on Exports
0 0 0 0 0 0 1 1 0 0 1	Test 2800	112.32	302137.76	0	506727.86	Competing Scenario
1 0 0 1 0 0 1 1 0 1 1	Test 2800	109.48	263844.24	4978644	388707.88	
0 1 0 0 1 0 1 1 0 1 1	Test 2800	108.24	239808.54	23233671	195125.95	
0 0 1 0 0 1 0 0 0 1 1	Test 2800	104.29	240525.45	46467341	-48871.87	
1 0 0 1 0 0 1 1 0 1 1	Test 2800	109.482	263844.2423	4978644	388707.8754	Zero Return on Exports
0 1 0 0 1 0 1 1 0 1 1	Test 2800	108.2409	239808.5433	23233671	195125.9468	Zero Return on Exports
0 0 1 0 0 1 0 0 0 1 1	Test 2800	106.7252	240525.4527	46467341	-48871.86824	Zero Return on Exports
1 0 0 1 0 0 1 1 0 1 1	MSTB	122.6219	27509.65596	4978644	-31792.83914	
1 0 0 1 0 0 1 1 0 1 1	MSTB	122.0184	27509.65596	4978644	-31792.83914	Ownership Type 2
1 0 0 1 0 0 1 1 0 1 1	SCAQMD	84.88167	52018.2851	4978644	-6915.286027	Ownership

						Type 2
0 0 1 0 0 1 1 1 0 1 1	LBVA	97.26365	450318.7242	46467341	152948.0512	Ownership Type 2
0 0 1 0 0 1 1 1 0 1 1	LBVA	85.48863	450318.7242	46467341	152948.0512	Ownership Type 3
1 0 0 1 0 0 1 1 0 1 1	MSTB	98.42518	27509.65596	4978644	-31792.83914	Ownership Type 3
1 0 0 1 0 0 1 1 0 1 1	SCAQMD	72.68314	52018.2851	4978644	-6915.286027	Ownership Type 3

Appendix B

Greenhouse Gas Emissions Calculation

Combined Output

Electricity = 1.4 MW_e

Chilling = 200 tons x 0.003516 MW_{th}/ton =0.7032 MW_{th}

Combined Output = 1.4 MW_e + 0.7032 MW_{th} = 2.1 $MW_{combined}$

Emissions Savings = 841.7* - 653.3** = 188.4 lb-CO_2/$MWh_{combined}$

Competing Scenario

Electricity: 1.4 MW_e x 1,100 lb/MWh_e = 1540 lb-CO_2/hr

Chilling: 200 tons x 0.003516 MW_{th}/ton x 1,100 lb/MWh_e ÷ COP = 227.5 lb-CO_2/hr

COP = (3.4 MW_{th} / 1 MW_e)

Total Emissions: 1,540 + 227.5 = 1,767.51 lb-CO_2/hr

Total Emissions Rate Using Combined Output: 1,767.51 lb-CO_2/hr ÷ 2.1 $MW_{combined}$

= 841.7 lb-CO_2/$MWh_{combined}$*

HTFC/AC

Electricity: 1.4 MWe x 980 lb/MWh_e = 1,372 lb-CO_2/hr

Chilling: 200 tons 0 lb/MWh_{th} = 0 lb-CO_2/hr

Total Emissions: 1372 lb-CO_2/hr

Total Emissions Rate Using Combined Output: 1,372 lb-CO_2/hr ÷ 2.1 $MW_{combined}$

= 653.3 lb-CO_2/$MWh_{combined}$**