Paper #4261

OPTIMIZATION OF NETWORKS OF DISTRIBUTED COMBINED HEAT AND POWER (CHP) FUEL CELL SYSTEMS (FCS) TO REDUCE GREENHOUSE GAS (GHG) EMISSIONS AND ENERGY COSTS

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Stationary combined heat and power (CHP) fuel cell systems (FCS) can provide electricity and heat for buildings, and can reduce greenhouse gas (GHG) emissions significantly if they are configured with an appropriate installation and operating strategy. The Maximizing Emission Reductions and Economic Savings Simulator (MERESS) optimization tool was developed and deployed to allow users to evaluate different strategies for installing and operating CHP FCS in buildings and towns. The MERESS model examines unique strategies that commercial industry has typically overlooked. It incorporates the pivotal choices made by FCS manufacturers, building owners, emission regulators, competing generators, and policy makers, and empowers them to evaluate the effect of their choices directly. The choice of operating strategy results in trade-offs among three important, but often competing goals: 1) GHG emission reductions, 2) cost savings to building owners in procuring electricity and heat, and 3) FCS manufacturer profitability. The MERESS model allows users to evaluate these design trade-offs and to identify the optimal control strategies and building load curves for installation based on either 1) maximum GHG emission reductions or 2) maximum cost savings to building owners. First, this work discusses the motivation and key assumptions behind MERESS model development. Second, it discusses run results from MERESS for a California town and makes recommendations for further FCS installments.

The research team deploys the MERESS model to show the impact of installing FCS in a California town. This town achieves the highest 1) GHG emission reductions, 2) cost savings to building owners, and 3) FCS manufacturer profitability with three different operating strategies. It achieves its maximum CO2 emission reduction, 37% relative to a base case of no FCS installed, with operating Strategy V: stand alone operation (SA), no load following (NLF), and a

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variable heat-to-power ratio (VHP) [SA, NLF, VHP]. The town's building owners gain the highest cost savings, 25% relative to a base case with no fuel cells and under full incentives and a $100/tonne CO2 tax, with Strategy I: electrically and thermally networked (NW), electricity power load following (ELF), and VHP [NW, ELF, VHP]. FCS manufacturers can be expected to have the highest profitability and sales with Strategy III: NW, NLF, with a fixed heat-to-power ratio (FHP) [NW, NLF, FHP]. Strategy III is consistent with the way that FCS manufacturers design their systems today, primarily as SA and NLF. Strategies I and V are avant-garde for the fuel cell industry, in particular, in their ability to operate FCS with a VHP. Without any state and federal incentives or carbon tax, Strategy I is economical, although marginally so, with 3% cost savings, and a 29% reduction in CO2 emissions. No particular building type stands out as consistently achieving the highest CO2 emission reductions or cost savings. However, buildings with load curves similar to a particular wet laboratory building (Mudd Chemistry) achieve maximal cost savings (1.5% with full federal and state incentives but no carbon tax) and maximal CO2 emission reductions (32%)

Keywords: Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*) optimization tool, fuel cell system (FCS), greenhouse gas emissions (GHG), carbon dioxide (CO_2) emissions, networks, cogeneration, combined heat and power (CHP), cost, profitability, thermal distribution networks, low-voltage electricity distribution networks, optimization, heat recovery, distributed energy systems, operating strategy, stand alone (SA), networked (NW), heat load following (HLF), electricity load following (ELF), no load following (NLF), variable heat-to-power ratio (VHP), fixed heat-to-power ratio (FHP).

1.0 Introduction

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

1.1. Purpose

The *MERESS* model expands the realm of possibilities for FCS installation and control by identifying and examining avant-garde design options, which commercial industry has not typically pursued [3]. FCSs can be installed and controlled using innovative designs, such as

- Stand alone (SA) or networked (NW),
- Heat load following (HLF), electricity load following (ELF), or no load following (NLF), and
- Variable heat-to-power ratio (VHP) [4,5] or fixed heat-to-power ratio (FHP).

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

The *MERESS* simulation and optimization tool was developed and deployed to allow users to evaluate different strategies for installing and operating distributed CHP FCSs in buildings. The *MERESS* model allows users to evaluate the electricity and heat supplied by networks of FCSs against real-time electricity and heating demand in buildings. The *MERESS* model combines 1) engineering data describing the real-world operation of FCSs [6, 7, 8, 9, 10] with 2) dynamic energy demand data from residences, office buildings, and industrial facilities [11, 12, 13]. The *MERESS* model allows users to evaluate the operation of these systems in different network configurations against the resultant change in GHG. The *MERESS* model allows a user to optimize the network's design either to minimize GHG emissions for electricity and heat provision or to minimize energy costs. The *MERESS* model empowers stakeholders to use relatively inexpensive simulation studies to identify more financially and environmentally effective ways to design and install FCS.

1.2. Objectives for Model Development

The goal of this model creation effort is to develop a simulation tool to evaluate the electricity and heat supplied by networks of FCSs against real-time electricity and heating demand in buildings. Towards this end, the *MERESS* model was developed to allow users to complete the following tasks:

1) Evaluate GHG emission reductions in five main types of buildings with the use of FCSs, so as to determine the most suitable building types for implementation.
2) Evaluate GHG emission reductions with different network configurations (stand alone or electrically and thermally networked, electrically or thermally load following, with a fixed or variable heat-to-power ratio), so as to determine the most suitable network designs.
3) Analyze GHG reductions in the context of costs.

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

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

The *MERESS* model was developed to test five different avant-garde installation and operating strategies. The underlying design options behind these strategies are explained in detail in Section **Error! Reference source not found.** ***Error!***

Reference source not found. on page **Error! Bookmark not defined.**. These 5 strategies are tested against a base case in which no FCSs are installed, and heat and power are provided exclusively by a competing generator or set of competing generators defined by the *MERESS* model's user.

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

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

2.0 Summary of Model Capabilities

MERESS allows users to evaluate avant-garde strategies for designing, installing, and controlling combined heat and power (CHP) fuel cell systems (FCSs). These strategies are summarized in **Table 1**. *MERESS* optimizes for either 1) maximum energy cost savings for building owners or 2) maximum reductions in greenhouse gas (GHG) emissions from energy use. *MERESS* includes input data describing electricity and heating load curves for buildings, FCS operating data, FCS financial data, government incentives, carbon taxes [14], and competing generator data. Users can base their analyses on accurate data already provided in the model or they can input their own. *MERESS* represents a significant improvement over previous models because 1) it models the FCSs within a broader economic and environmental context including their interactions with competing generators and emission taxes, and 2) it includes technically and economically accurate descriptions of FCSs, and 3) it allows users to evaluate avant-garde design strategies typically overlooked by industry. This work next discusses run results from *MERESS* for a particular California town and, based on these results, makes recommendations for increasing the deployment of FCS for reducing GHG emissions and energy costs.

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

Table 1. Operating strategies modeled

3.0 Research Objectives

The primary research objective presented in this work is to conduct a case study for optimally deploying stationary combined heat and power (CHP) fuel cell systems (FCSs) in a California town. The Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*) model is deployed to identify the most financially and environmentally beneficial strategies for designing, installing, and controlling FCSs within this town's complex of buildings. *MERESS* is used to evaluate one of the most challenging FCS types to use for greenhouse gas (GHG) reductions, the Phosphoric Acid Fuel Cell (PAFC) system. (These systems have relatively low electrical efficiencies (~40%) compared with some other FCS types (~60%); as a result, they must effectively recover heat to achieve high overall (thermal plus electrical) efficiencies and to reduce GHG emissions.) These PAFC FCSs are tested against a base case of a high performance CHP combined cycle natural gas turbine (CCGT). The strategies investigated are avant-garde, and are summarized in **Table 1**. Five scenarios (A through E) evaluate the effect of a changing carbon tax and changing government incentives on the optimal installation strategies (I through V). The input parameters for these five scenarios (A through E) are summarized in **Table 2**. As the scenarios progress from A to E, the extent of the carbon tax or government incentive increases. Within each scenario, strategies are compared. A secondary research objective is to apply the results from these model runs to identify general recommendations for building owners, policy makers, and FCS manufacturers for reducing emissions with FCSs.

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

Key Assumptions:
base case = no fuel cells, all CHP combined cycle gas turbine plant
common fuel for fuel cells and turbine = natural gas
base case electricity and heating costs (no fuel cells) = $20 million/yr
cost of capital (r) = 7.42% = educational borrowing rate ≈ bond rate
fuel cell turn-key cost (without incentives) = $6,200/kWe
* fuel cell incentives: $2,500/kWe (state); $1,000/kWe (federal)
free market price of natural gas = $8.95/million BTU
** natural gas price with CHP incentive = $7.45/million BTU

Legend:
solid yellow = highest energy cost savings
slashed blue = highest sales / fuel cell manufacturer profit
counter-slashed green = highest CO_2 emission reductions

Table 2. Key inputs and results for scenario runs

4.0 Research Outcomes

Table 2 summarizes results by listing the best strategies for meeting each of three competing goals (GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue) for each scenario.

Model results demonstrate that FCS installations can be economical for building owners without any carbon tax or government incentives. Scenario A examines the case of no state or federal incentives or a carbon tax. Without any carbon tax or state and federal incentives (Scenario A), Strategy I [electrically and thermally networked (NW), electricity load following (ELF), variable heat-to-power ratio (VHP)] is marginally economical, with 3% energy cost savings, but with a 29% reduction in carbon dioxide (CO_2) emissions. Strategy I is avant-garde for the fuel cell industry, in particular, in its use of a VHP and thermal networking.

Also in the case of no carbon tax or government incentives (Scenario A), all three competing goals (GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue) are best achieved with a single approach (Strategy I). Strategy I achieves the highest reductions in CO_2 emissions, and also shows the most installations or sales, 17% of the total average electrical power installed in the geographic area. (Producers typically associate increasing sales revenue with profit maximization.) **Figure 1** summarizes these results for Scenario A.

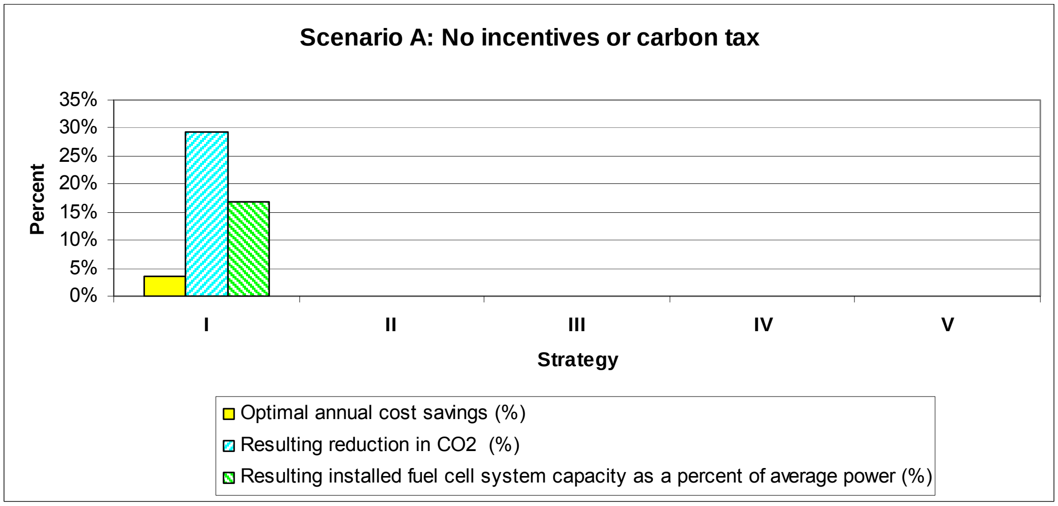

Figure 1: Summary of Scenario A results

- Under scenarios with high carbon taxes and large government incentives, the three competing goals (GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue) may be best achieved with different strategies. Figure 2 summarizes results for Scenario D, a scenario with full state and federal incentives and a \$100/tonne CO2 tax. The town achieves the highest 1) GHG emission reductions, 2) cost savings to building owners, and 3) FCS manufacturer sales revenue each with three different operating strategies. The town achieves its maximum CO2 emission reduction, 34% relative to the base case, with operating Strategy V: stand alone operation (SA), no load following (NLF), and a fixed heat-to-power ratio (FHP) [SA, NLF, FHP]. Most prototype FCSs today are installed according to Strategy V, so in many ways this represents a status-quo installation strategy, and therefore a benchmark against which to compare the performance of other strategies. The town's building owners gain the highest cost savings, 25%, with Strategy I. Again, Strategy I is an avant-garde installation strategy, in particular for its use of a VHP and thermal networking. FCS manufacturers have the highest sales revenue, under which FCSs provide 60% of average electrical power capacity, with Strategy III [NW, NLF, FHP]. Strategy III is partly consistent with the way that FCS manufacturers design their systems today, primarily as NLF with a FHP.
- Under these scenarios with high carbon taxes and large government incentives, all three goals may be met reasonably well with a single

approach. For Scenario D, Figure 2 shows that Strategy I achieves all three goals to a reasonable extent. Strategy I has the highest annual cost savings, nearly the highest CO2 reductions, and a fair amount of sales revenue.

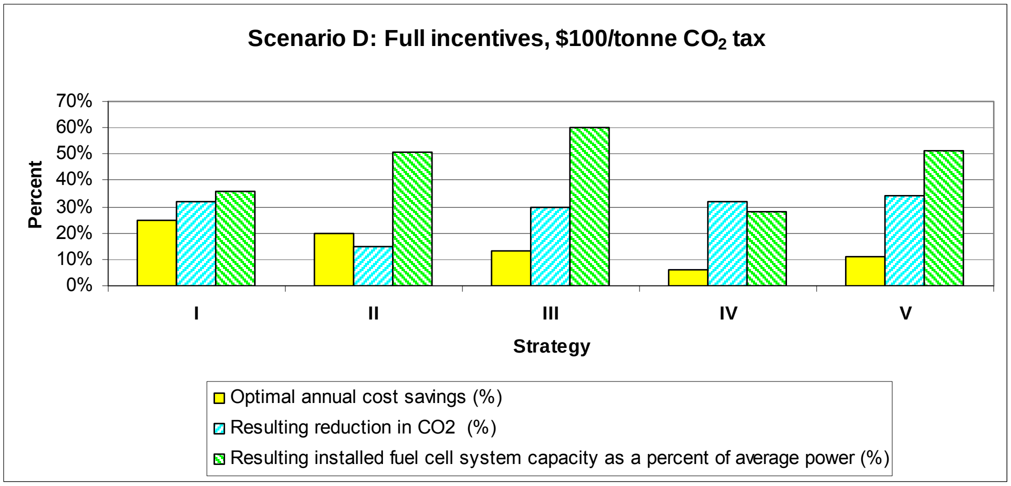

Figure 2: Summary of Scenario D results

- Throughout all scenarios (Scenarios A through D), regardless of the level of carbon tax or government incentives, Strategy I is the most economical strategy for building owners. At the same time, it reasonably achieves other goals of GHG emission reductions and FCS manufacturer sales revenue. Figures 1 and 2 above demonstrate this for Scenarios A and D. Figures 3 and 4 below show this for Scenarios B and C.
- Scenario B examines the case of full state and federal incentives, but no carbon tax. In Scenario B, Strategy I again achieves the highest annual energy cost savings, 15% relative to the base case, and the highest reduction in CO2 emissions, 31% relative to the base case. By contrast, Strategy III [NW, no load following (NLF), fixed heat-to-power ratio (FHP)] achieves the highest number of installations, 46% of average electrical power installed. This comparison illustrates a dichotomy between the most economical strategy for building owners and the most economical strategy for fuel cell manufacturers.

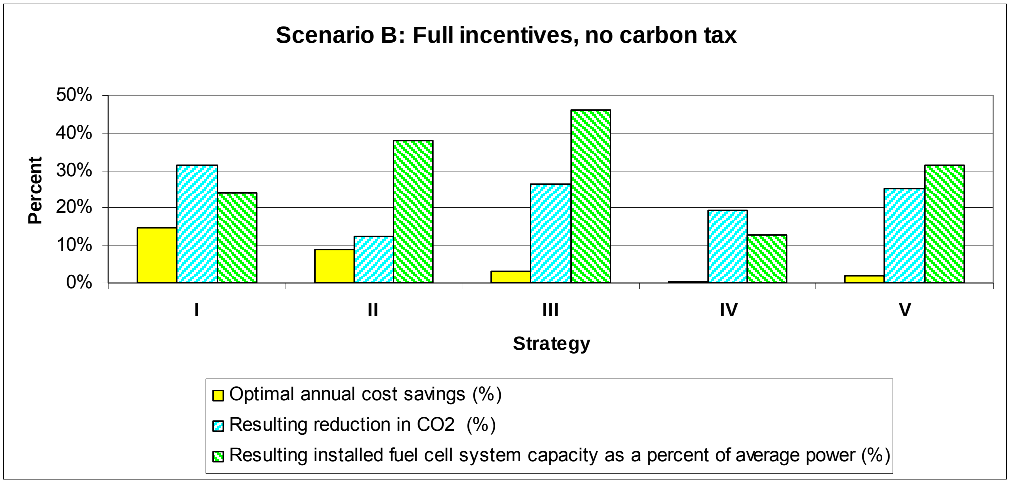

Figure 3: Summary of Scenario B results

- Scenario C examines the case of full state and federal incentives and a \$20/tonne CO2 tax. In Scenario C, Strategy I again achieves the highest annual energy cost savings, 17% relative to the base case, and the highest reduction in CO2 emissions, 33% relative to the base case. By contrast, Strategy III again achieves the highest number of installations, 49% of average electrical power installed. Between Scenario B and Scenario C, the results do not change much; a \$0/tonne CO2 tax has nearly the same effect as a \$20/tonne CO2 tax. The carbon tax drives up both the FCS and competing generator running costs in a similar manner.

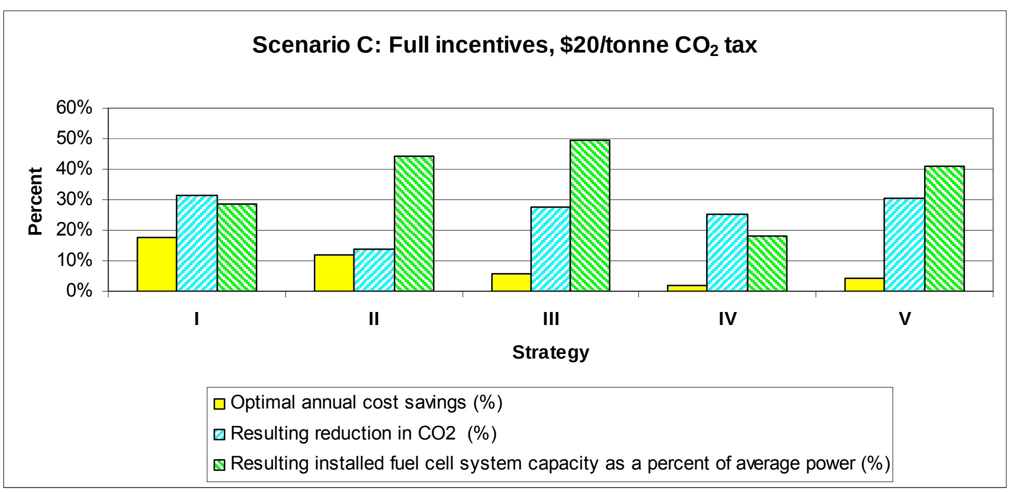

Figure 4: Summary of Scenario C results

- FCS installations reduce CO2 emissions the most with a status-quo installation strategy. Model results show that the town achieves its maximum CO2 emission reduction, 37% relative to the base case, with

Strategy V [SA, NLF, FHP]. This result is shown by Scenario E and in Figure 5 below. Scenario E examines the case of an unrealistically high carbon tax ($1,000,000/tonne CO2) so as to alter the function of the model such that the model optimizes not for the highest financial savings, but rather the highest reduction in CO2 emissions. The results for Scenario E demonstrate that the strategies that achieve the highest reductions in CO2 emissions are Strategies I, III, and V. Of these, Strategy V achieves the maximum reduction in CO2 emissions, although Strategies I and III are not far behind. Among Strategies I, III, and V, Strategy III leads to higher sales for FCS manufacturers.

- The strategy with the highest sales for FCS makers also has to the highest emissions. Strategy II leads to the absolute highest FCS sales for fuel cell manufacturers, but the lowest absolute CO2 emission reductions. This result is shown in Figure 5.

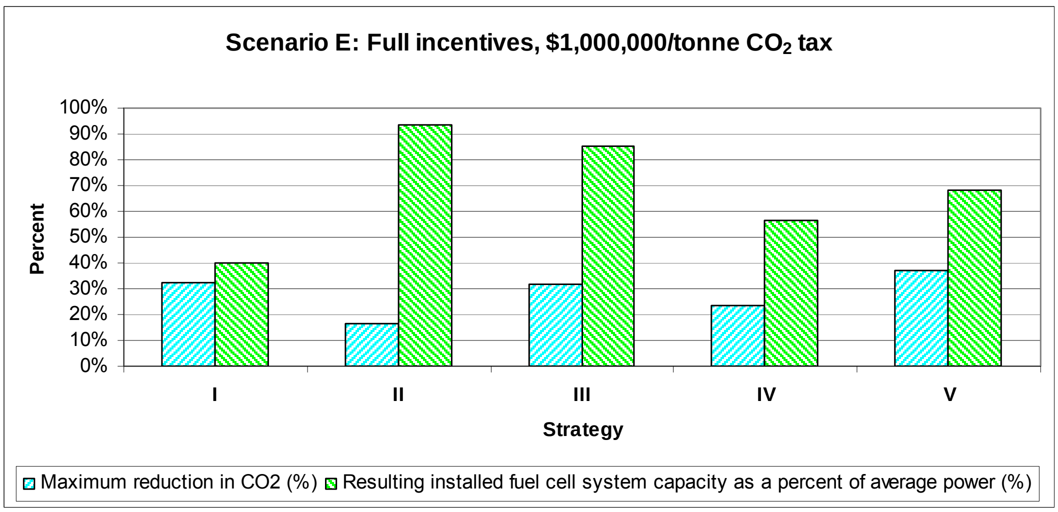

Figure 5: Summary of Scenario E results: Highest CO_2 Emission Reductions

- Although no particular building type stands out as consistently achieving the highest emission reductions and cost savings (Scenarios B-2 and E-2), certain building load curves are clear winners. For example, buildings with load curves similar to Stanford's Mudd Chemistry building (a wet laboratory) achieve maximal cost savings (1.5% with full federal and state incentives but no carbon tax) and maximal CO2 emission reductions (32%) (Scenarios B-2 and E-2).
- Under Scenario B, if either Strategies IV [SA, heat load following (HLF), VHP] or V [SA, NLF, FHP] are implemented, then the most economical installations in both cases are wet laboratory buildings. (Wet laboratories are buildings designed to handle multiple experimental set-ups involving chemicals, drugs, biological matter, and/or electronics, which require specialized piped utilities, direct ventilation, exhaust fume extractors,

workbenches designed for noxious fumes, dust control, and/or temperature-and humidity-sensitive heating, ventilating, and air-conditioning (HVAC) systems. They include biology and chemistry labs.)

- Results from the various scenarios are compared visually in Figures 16 and 17. Figure 6 plots optimal energy cost savings against carbon tax. Figure 7 plots the resulting installed capacity against carbon tax.

5.0 Conclusions

In evaluating GHG emission reductions with the use of FCSs in buildings, this work makes several conclusions:

- The electricity and heating load curves of individual buildings are extremely important in determining the economics and GHG emission reduction from an installation.
- These load curves are extremely important because the strategy that achieves the highest reductions in CO2 emissions is with SA operation, in which one or a few FCSs manipulate their operation to meet the instantaneous electricity and heating demand from these buildings described by their load curves, without additional back-up or buffer of a surrounding electrical or thermal network.
- Specifically, the highest reductions in CO2 emissions were observed with Strategy V, which incorporates SA operation, HLF, and with a FHP.
- For this stand alone strategy (Strategy V), the best building load curves for maximum CO2 reductions were identified. The top three of these load curves were those for Stanford's Seeley G. Mudd Chemistry building, the Braun Music building, and the Edward L. Ginzton Labs and Annex.
- No particular building type (such as a wet laboratory or residence) stands out as maximizing any of these three goals consistently, across strategies: GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue.
- This last point above underscores the pivotal role that the MERESS model can play in being able to test out a particular building's load curves.
- In evaluating GHG emission reductions with the use of FCSs under different network configurations, for the buildings and town evaluated here, this work makes several conclusions:
- Under Scenario D, with full government incentives and a $100/tonne CO2 tax, three different strategies achieve the highest GHG emission reductions, cost savings to building owners, and FCS manufacturer profitability.
- Strategy V achieves the highest reductions in CO2 emissions.

- Strategy I provides energy for building owners with the lowest total cost, including the fixed and variable costs of resources and fuel over the investment time horizon.
- Strategy III provides the highest sales revenue for fuel cell manufacturers
- Under Scenario A, without any state and federal incentives or carbon tax, Strategy I is economical, although marginally so. The significance of this finding is to demonstrate that just by changing the installation and operating strategy for FCSs, they can be installed economically, without any governmental incentives. FCSs have not typically been designed and installed to be connected to thermal networks, to follow electrical loads, and to achieve a VHP, either separately or in concert. This combined scenario and strategy demonstrate that FCSs can outperform conventional heat and electricity generation if they are built to provide both electricity and heat through CHP, operate at some fraction of total energy demand in a geographic area, and are connected to a pre-existing thermal network (district heating pipelines).
- The strategies that achieve the highest cost savings for building owners differ greatly from the strategies that achive the highest FCS manufacturer sales revenue.
- Strategies III and V are consistent with the way that FCS manufacturers design their systems today, primarily as NLF with a FHP. Most prototype FCSs today are installed as SA, NLF, and FHP, or according to Strategy V above. In this way, Strategy V acts as a benchmark of status quo designs against which to compare the performance of other strategies.
- By contrast, Strategy I is avant-garde for the fuel cell industry, in particular, in its use of a VHP. These results suggest that fuel cell developers and building owners could benefit by thinking outside of the box.
- In all scenarios evaluated, higher energy cost savings are achieved with linking FCSs together in electrical and thermal networks, as opposed to installing them SA.
- NW, combined with either electrical or thermal load following and VHP, improved economic performance.

6.0 Recommendations

In the course of developing these conclusions, this work identifies four key recommendations for policy makers for encouraging industry and property owners to implement distributed energy networks that reduce GHG emissions:

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

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

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

7.0 Benefits From this Work

Several benefits have already been received from this work:

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

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