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PART II OF II: DEPLOYMENT OF *MERESS* MODEL -- DESIGNING, CONTROLLING, AND INSTALLING STATIONARY COMBINED HEAT AND POWER (CHP) FUEL CELL SYSTEMS (FCS) TO REDUCE COSTS AND GREENHOUSE GAS (GHG) EMISSIONS

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ABSTRACT
The Maximizing Emission Reductions and Economic Savings Simulator (MERESS) is an optimization tool that allows users to evaluate avant-garde strategies for installing and operating combined heat and power (CHP) fuel cell systems (FCSs) in buildings. This article discusses the deployment of MERESS to show illustrative results for a California campus town, and, based on these results, makes recommendations for further installations of FCSs to reduce greenhouse gas (GHG) emissions. MERESS is used to evaluate one of the most challenging FCS types to use for GHG reductions, the Phosphoric Acid Fuel Cell (PAFC) system. These PAFC FCSs are tested against a base case of a CHP combined cycle gas turbine (CCGT). Model results show that three competing goals (GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue) are best achieved with different strategies, but that all three goals can be met reasonably with a single approach. According to MERESS, relative to a base case of only a CHP CCGT providing heat and electricity with no FCSs, 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, under a scenario of full incentives and a \$100/tonne carbon dioxide (CO_2) tax (Scenario D). The town achieves its maximum CO_2 emission reduction, 37% 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] (Scenario E). The town's building owners gain the highest cost savings, 25%, with Strategy I: electrically and thermally networked (NW), electricity power load following (ELF), and a variable heat-to-power ratio (VHP) [NW, ELF, VHP] (Scenario D). FCS manufacturers generally have the highest sales revenue with Strategy III: NW, NLF, with a fixed heat-to-power ratio (FHP) [NW, NLF, FHP] (Scenarios B, C, and D). Strategies III and V are partly consistent with the way that FCS manufacturers design their systems today, primarily as NLF with a FHP. By contrast, Strategy I is avant-garde for the fuel cell industry, in particular, in its use of a VHP and thermal networking. Model results further demonstrate that FCS installations can be economical for building owners without any carbon tax or government incentives. Without any carbon tax or state and federal incentives (Scenario A), Strategy I is marginally economical, with 3% energy cost savings, but with a 29% reduction in CO_2 emissions. Strategy I is the most economical strategy for building owners in all scenarios (Scenarios A, B, C, and D) and, at the same time, reasonably achieves other goals of large GHG emission reductions and high FCS manufacturer sales revenue. 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 CO_2 emission reductions (32%) (Scenarios B-2 and E-2). Finally, based on these results, this work makes recommendations for reducing GHG further through FCS deployment. (Part I of II articles discusses the motivation and key assumptions behind the MERESS model development (Colella 2008).)

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 SUMMARY

The article first summarizes research objectives, results, and final recommendations in this summary section and then discusses these results in detail in subsequent sections.

Research Objectives

The primary research objective presented in this article 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 and in Part I of the two part article series (Colella 2008). 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.

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

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 green = highest sales / fuel cell manufacturer profit
counter-slashed blue = highest CO_2 emission reductions

Table 2. Key inputs and results for scenarios

Research Outcomes

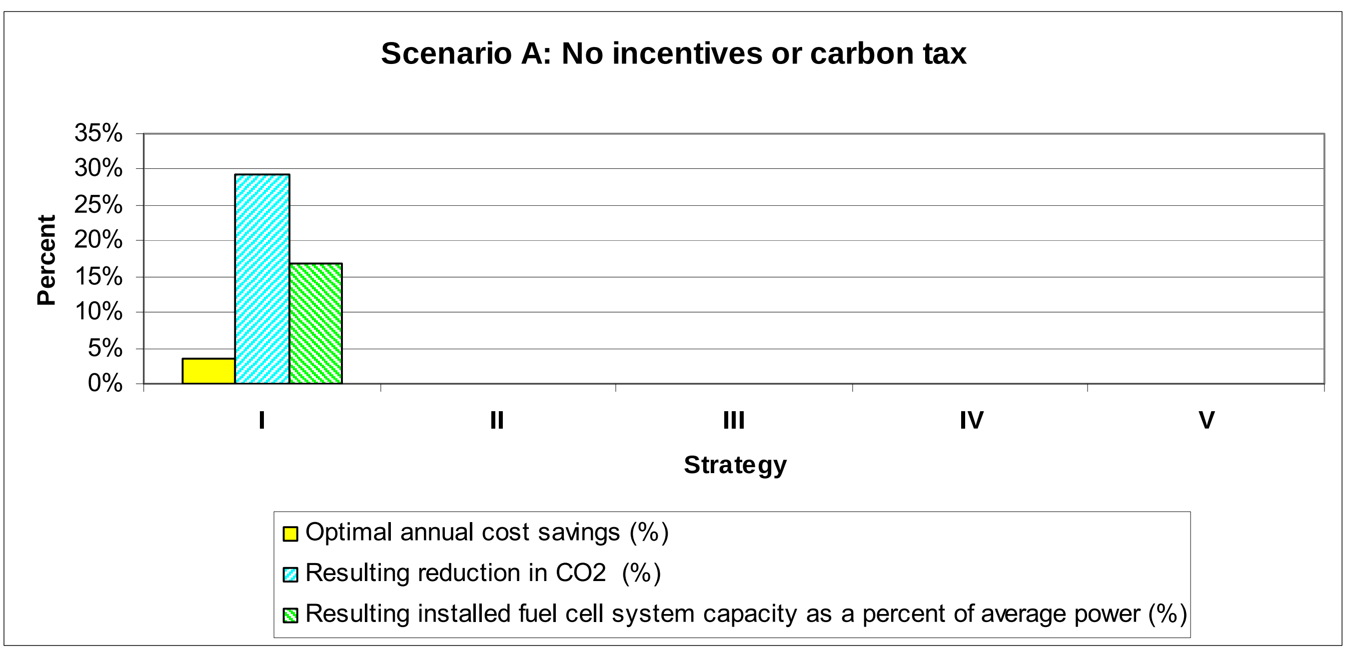
Table 2 summarizes results by listing the best strategies for meeting each of three competing goals (GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue) for each scenario.

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. (By contrast, previous investigations of using FCSs to reduce CO_2 emissions have typically focused on stand-alone operation only (Bizzarri 2004), on variations of a single FCS's design (Jahnke 2004), or on optimization of a single FCS's design for electrical efficiency only (Yi 2004, Roberts 2006).)

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.

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 CO_2 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 CO_2 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

Figure 1: Summary of Scenario A results



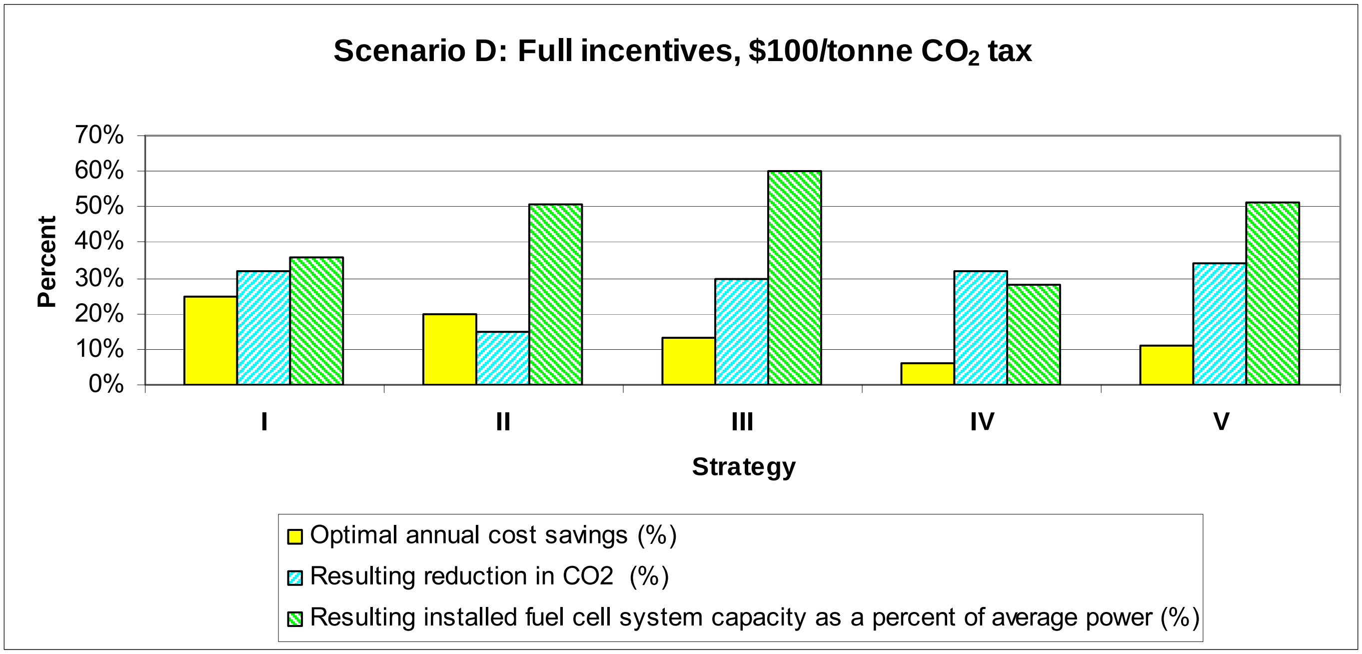
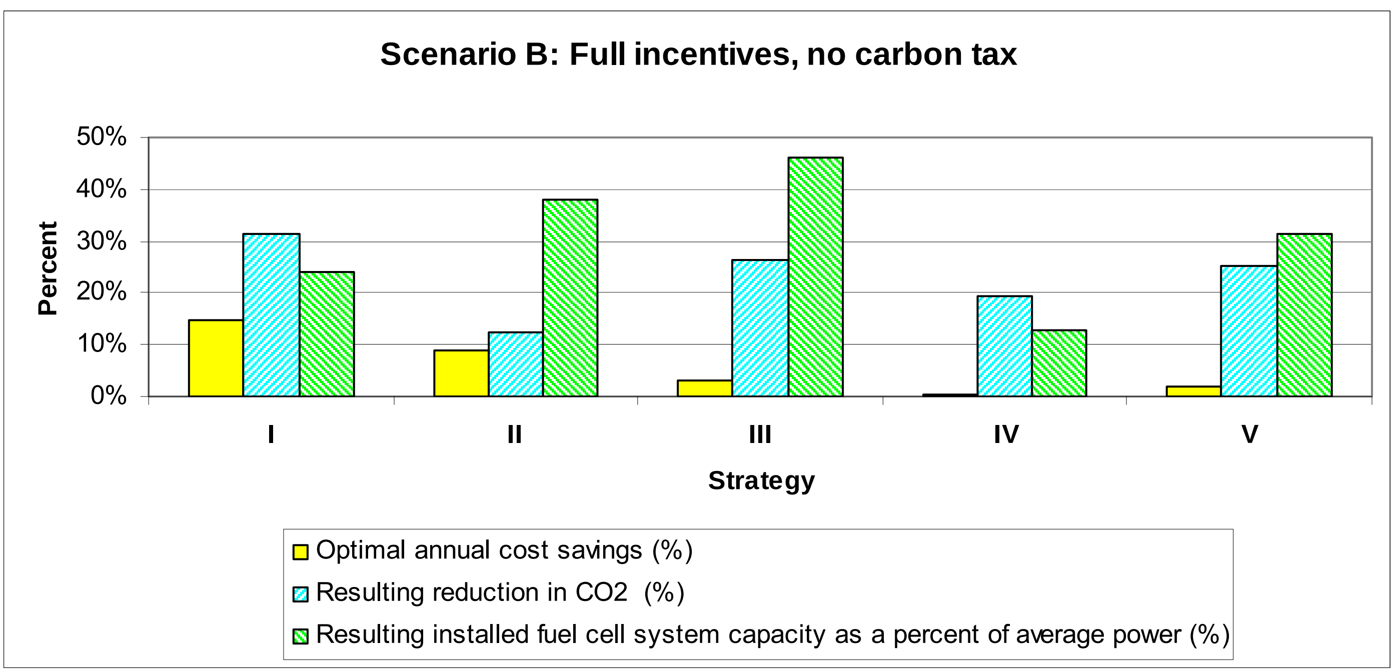


Figure 2: Summary of Scenario D results

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 CO_2 reductions, and a fair amount of sales revenue. 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.

Figure 3: Summary of Scenario B results



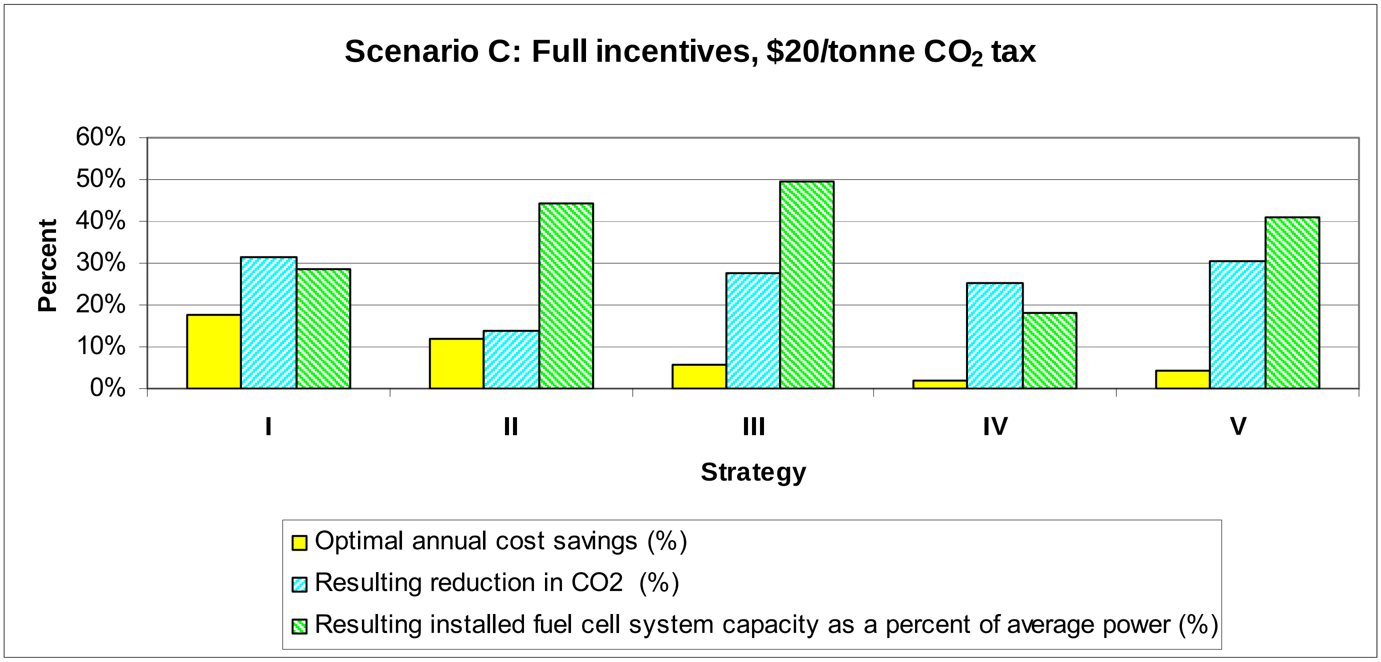


Figure 4: Summary of Scenario C results

Scenario B examines the case of full state and federal incentives, but no carbon tax. In Scenario B, Strategy I again achieves the highest annual energy cost savings, 15% relative to the base case, and the highest reduction in CO_2 emissions, 31% relative to the base case. By contrast, Strategy III [NW, 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.

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

FCS installations reduce CO_2 emissions the most with a status-quo installation strategy. Model results show that the town achieves its maximum CO_2 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 CO_2) so as to alter the function of the model such that the model optimizes not for the highest financial savings, but rather the highest reduction in CO_2 emissions. The results for Scenario E demonstrate that the strategies that achieve the highest reductions in CO_2 emissions are Strategies I, III, and V. Of these, Strategy V achieves the maximum reduction in CO_2 emissions, although Strategies I and III are not far behind. Among Strategies I, III, and V, Strategy III leads to higher sales for FCS manufacturers.

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 CO_2 emission reductions. This result is shown in Figure 5.

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 CO_2 emission reductions (32%) (Scenarios B-2 and E-2).

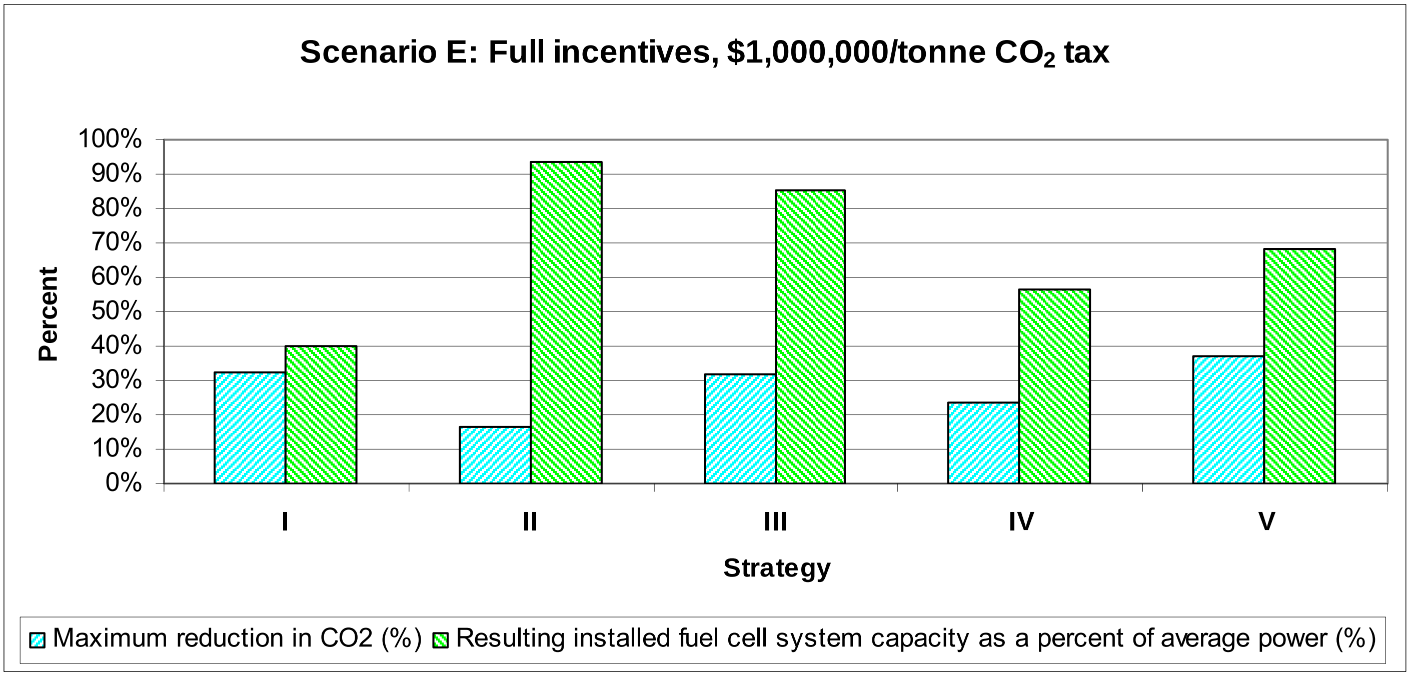


Figure 5: Summary of Scenario E results

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 6 and 7. Figure 6 plots optimal energy cost savings against carbon tax. Figure 7 plots the resulting installed capacity against carbon tax.

Conclusions

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

- The electricity and heating load curves of individual buildings are extremely important in determining the economics and GHG emission reduction from an installation.
- These load curves are extremely important because the strategy that achieves the highest reductions in CO_2 emissions is with SA operation, in which one or a few FCSs manipulate their operation to meet the instantaneous electricity and heating demand from these buildings described by their load curves, without additional back-up or buffer of a surrounding electrical or thermal network.
- Specifically, the highest reductions in CO_2 emissions were observed with Strategy V, which incorporates SA operation, HLF, and with a FHP.
- For this stand alone strategy (Strategy V), the best building load curves for maximum CO_2

reductions were identified. The top three of these load curves were those for Stanford's Seeley G. Mudd Chemistry building, the Braun Music building, and the Edward L. Ginzton Labs and Annex.

- No particular building type (such as a wet laboratory or residence) stands out as maximizing any of these three goals consistently, across strategies: GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue.
- This last point above underscores the pivotal role that the *MERESS* model can play in being able to test out a particular building's load curves.
- In evaluating GHG emission reductions with the use of FCSs under different network configurations, for the buildings and town evaluated here, the article makes several conclusions:
- Under Scenario D, with full government incentives and a $100/tonne CO_2 tax, three different strategies achieve the highest GHG emission reductions, cost savings to building owners, and FCS manufacturer profitability.
- Strategy V achieves the highest reductions in CO_2 emissions.
- Strategy I provides energy for building owners with the lowest total cost, including the fixed and variable costs of resources and fuel over the investment time horizon.
- Strategy III provides the highest sales revenue for fuel cell manufacturers
- Under Scenario A, without any state and federal incentives or carbon tax, Strategy I is economical, although marginally so. The significance of this finding is to demonstrate that just by changing the installation and operating strategy for FCSs, they can be installed economically, without any governmental incentives. FCSs have not typically been designed and installed to be connected to thermal networks, to follow electrical loads, and to achieve a VHP, either separately or in concert. This combined scenario and strategy demonstrate that FCSs can outperform conventional heat and electricity generation if they are built to provide both electricity and heat through CHP, operate at some fraction of total energy demand in a geographic area, and are connected to a pre-existing thermal network (district heating pipelines).
- The strategies that achieve the highest cost savings for building owners differ greatly from the strategies that achieve the highest FCS manufacturer sales revenue.
- Strategies III and V are consistent with the way that FCS manufacturers design their systems today, primarily as NLF with a FHP. Most prototype FCSs today are installed as SA, NLF, and FHP, or according to Strategy V above. In this way, Strategy V acts as a benchmark of status quo designs against which to compare the performance of other strategies.
- By contrast, Strategy I is avant-garde for the fuel cell industry, in particular, in its use of a VHP. These results suggest that fuel cell developers and building owners could benefit by thinking outside of the box.
- In all scenarios evaluated, higher energy cost savings are achieved with linking FCSs together in electrical and thermal networks, as opposed to installing them SA.
- NW, combined with either electrical or thermal load following and VHP, improved economic performance.

Recommendations

In the course of developing these conclusions, the article 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.

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 article 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.

2.0 DATUM DESIGN CONDITIONS

These *MERESS* model runs presented here rely on the same input data included in *MERESS* model and discussed in detail in the initial Part I article (Colella 2008). This data includes building load curve data, FCS operating data, FCS financial data, government incentive data, carbon tax assumptions, and competing generator data. Although users can change this input data to tailor the *MERESS* model for their own purposes, the results presented here rely on the datum design conditions already included in the model and presented in Part I. For the results presented, the systems are assumed to be installed in a California campus town, modeled after the Stanford campus, referred to as Campustown in this text. Specific state and federal incentives apply to FCS in California, as specified in Part I. These model runs also assume the financial and technical performance of the Phosphoric Acid Fuel Cell (PAFC) systems presented in Part I. 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 financial and technical performance of the CCGT was also specified in Part I.

3.0 RESULTS

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

Simulation results are presented in **Table 3** for the scenario in which no state or federal incentives or carbon tax are applied for installing fuel cell or CHP systems. The base case refers to a scenario in which no FCSs are installed, and heat and power are provided exclusively by the competing generator.

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

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

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

$$Profit = Sales\ Revenue - Costs.$$

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

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

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

Another significant outcome of this scenario run is to demonstrate that just by changing the installation and operating strategy approach to FCSs, they can be installed economically, without any governmental incentives. FCSs have not typically been designed and installed to be connected to thermal networks, to follow electrical loads, and to achieve a VHP, either separately or in concert. This scenario run demonstrates that

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

Table 3. Simulation results for a scenario with no incentives

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

Table 4. Simulation results for a scenario with government incentives

locations with pre-existing thermal networks (district heating pipes) are excellent retrofit candidates for CHP FCSs.

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

Table 4 shows simulation results for the scenario in which full state and federal incentives are applied, but no carbon tax is applied. These incentives were discussed in the previous article in the section on **Error! Reference source not found.** (Colella 2008). The most economical strategy for Campustown is again Strategy I [NW, ELF, VHP] (highlighted in yellow), which has an annual energy cost savings of 15%, with FCSs installed at an electrical capacity of 24% of average electrical power. Strategy I also achieves the highest reduction in CO_2 emissions, 31% relative to the base case. By contrast, the most economical strategy for the fuel cell manufacturer is different. As mentioned, producers usually associate profit maximization with maximal sales. The operating strategy that results in the most sales of FCSs is Strategy III [NW, NLF, FHP] (highlighted in green), with 44 systems or 46% of average electrical power installed. Strategy III also achieves the second highest reduction in CO_2 emissions, 27% relative to the base case. However, this strategy results in an annual energy cost savings of only 3% for Campustown. These simulations illustrate a striking dichotomy between the most economical strategy for building owners and the most economical strategy for fuel cell manufacturers, although both achieve significant reductions in CO_2. This financial dichotomy pervades most scenarios.

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

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

Table 4 also indicates that networking fuel cells thermally and electrically is more economical than not networking them. The NW strategies (I, II, III) all achieve higher savings than the SA strategies (IV, V). Networking has the highest savings most likely due to the resulting load leveling effect. Load leveling increases system capacity utilization.

Table 4 also shows that when there is networking (Strategies I, II and III), fuel cells are more economical if they combine either electrical or thermal load following with a VHP (Strategies I and II). Table 4 indicates that, for the assumptions of this analysis, when fuel cells are operating SA, they are more economical if they combine NLF with FHP (Strategy V). The *MERESS* model can be extended to test additional configurations, such as synergies with plug-in hybrid vehicles and electrical storage.

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

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

For FCSs that are operated as SA, the relative economics of installing a system in one building versus another depends on an individual building's electricity and heating demand curves over time. In the case that Strategy IV is implemented, Table 5 shows the only economical installations, grouped according to building type and by the building name with the most similar load curve to that modeled. The load curve tested for each building is a scaled up version of the load curve of the underlying sample building. Of the 30 building load curves investigated, only 6 are economical, and only marginally; these are wet laboratories and dry laboratories. Of these, the one that is most economical for Campustown is the building load curve most similar to that of the Mudd Chemistry building, a

Strategy IV: Most Economical Buildings for Installations

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

Strategy V: Most Economical Buildings for Installations

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

Table 5. Most economical building load curves with SA installation

wet laboratory, with a 1.5% savings (highlighted in yellow). The most economical installation for fuel cell manufacturers is in buildings with load curves most similar to either Mudd Chemistry building or the Center for Integrated Systems (CIS), a wet laboratory (highlighted in green). To generalize these results for a larger audience, consider that wet and dry laboratories are similar in their energy requirements to many industrial facilities, which also operate around-the-clock at high energy consumption levels. In the case that Strategy V is implemented, Table 5 shows the economical installations, by building type and by the building name with the most similar load curve to that modeled. Of the 30 building load curves investigated, only 12 are marginally economical. Of these, the one that is most economical for Campustown is the load curve most similar to the McCullough building, a dry laboratory, with a 3.5% savings (highlighted in yellow). The most economical installation for fuel cell manufacturers is the load curve most similar to the Center for Integrated Systems (CIS), a wet laboratory (highlighted in green), with 9 systems installed supplying electrical capacity for 9% of average electrical demand. The most common building type among the economical group is the dry laboratory. The remainders span the range of building types, from wet laboratories, to museums/libraries, housing facilities, to offices and classrooms. These results underscore the importance of testing the FCS's performance against the particular load curves of the buildings they may serve, rather than generalizing by building type alone.

Table 6. Simulation results with government incentives and \$20/tonne CO_2 carbon tax

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

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

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

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

Simulation results are shown in Table 7 for the scenario in which full state and federal incentives are applied, as well as a carbon tax at \$100/tonne CO_2. The most economical strategy remains Strategy I for Campustown and Strategy III for fuel cell manufacturers. As the carbon tax increases from \$0 to \$100/tonne CO_2, the top-most preferred strategy for each player (building owner or manufacturer) remains the same, and the optimal quantity of installations and resulting savings increase. By contrast, the most environmentally benign strategy changes from Strategy **I** to Strategy V (highlighted in blue). Strategy V achieves the highest reduction in CO_2 emissions, 34% of the base case.

Table 7. Simulation results with government incentives and \$100/tonne CO_2 carbon tax

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

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

Summary Trends Based on Scenarios B, C, and D

Figure 6 shows the maximum cost savings to building owners in Campustown with the optimal quantity of FCSs installed across a range of carbon tax levels, for each of the five scenarios. The maximum savings is shown as a percentage of the base case costs with no fuel cells. The figure plots the data points for \$0, \$20, and \$100/tonne of CO_2 presented in previous tables and connects them with a curve fit. Regardless of carbon tax level, building owners save the most money by installing systems with Strategy **I**.

Figure 7 shows the optimal installed electrical capacity of FCSs as a percentage of total average electrical demand in Campustown across a range of carbon tax levels, for each of the five scenarios. Again, the figure plots the data points for \$0, \$20, and \$100/tonne of CO_2 presented in previous tables and connects them with a curve fit. Manufacturers typically associate profit maximization with maximal sales, or, in this case, installed capacity. A manufacturer achieves the highest sales with Strategy **III**, regardless of carbon tax level**.** Strategy **II** results in the second highest sales, initially. At higher carbon tax levels (around \$85/tonne of CO_2, Strategy V results in the second highest sales.

A comparison of **Figures 6** and **7** underscores an important difference between the most economical installation and control strategies for building owners and that for fuel cell manufacturers. Resolving these diverse incentives could facilitate more effective system deployments and lower aggregate GHG emissions.

Figure 7 leads to an important conclusion for policy makers about the nature and extent of the subsidies they may consider: policy makers may be able to increase FCS penetration more effectively by incentivizing certain types of strategies over others, rather than by instituting a large carbon tax. For example, for the analysis described here, moving from zero carbon tax to a \$100/tonne carbon tax can increase the number of FCS installations under Strategy IV (bottom line) from 13% to 28% average capacity. By contrast, persuading manufacturers and building owners to switch from Strategy IV

Figure 6. Best strategies for cost savings for building owners

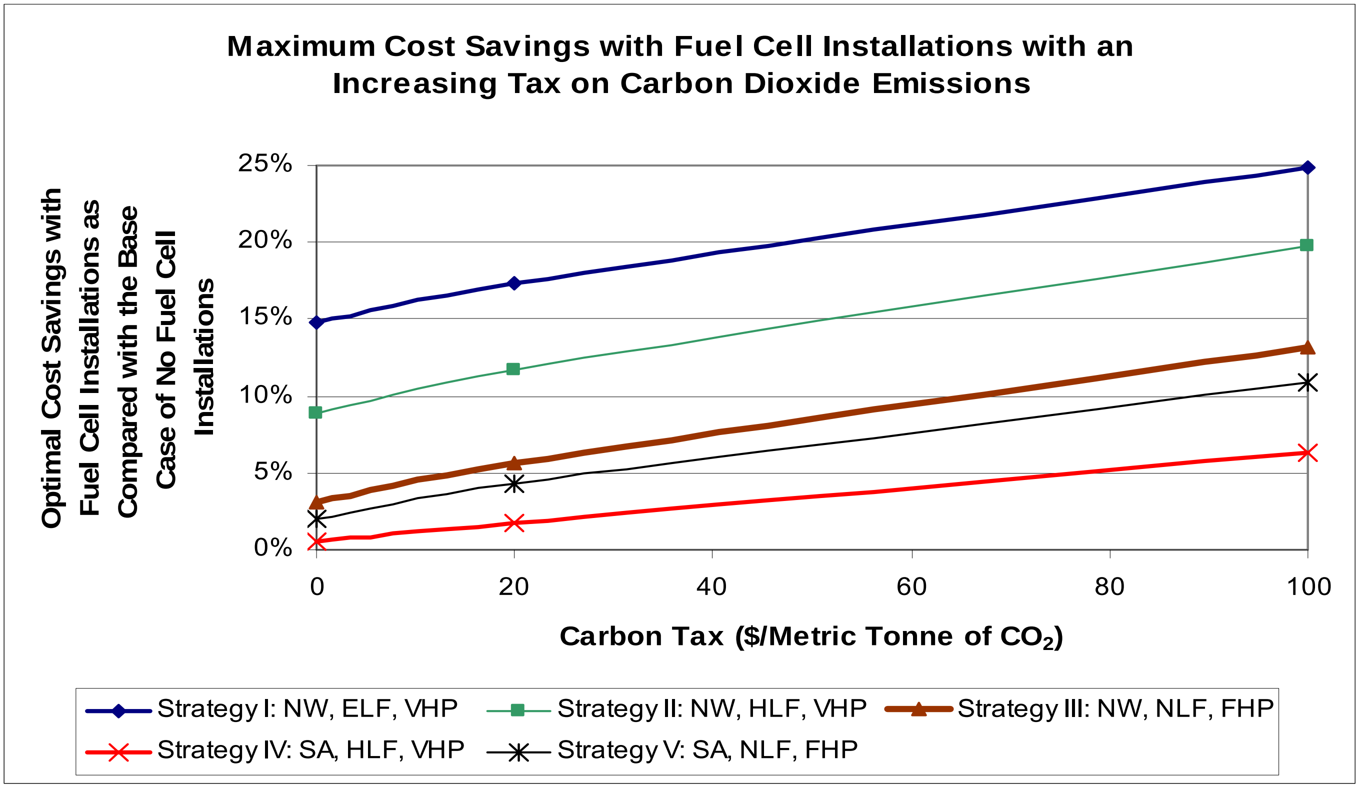
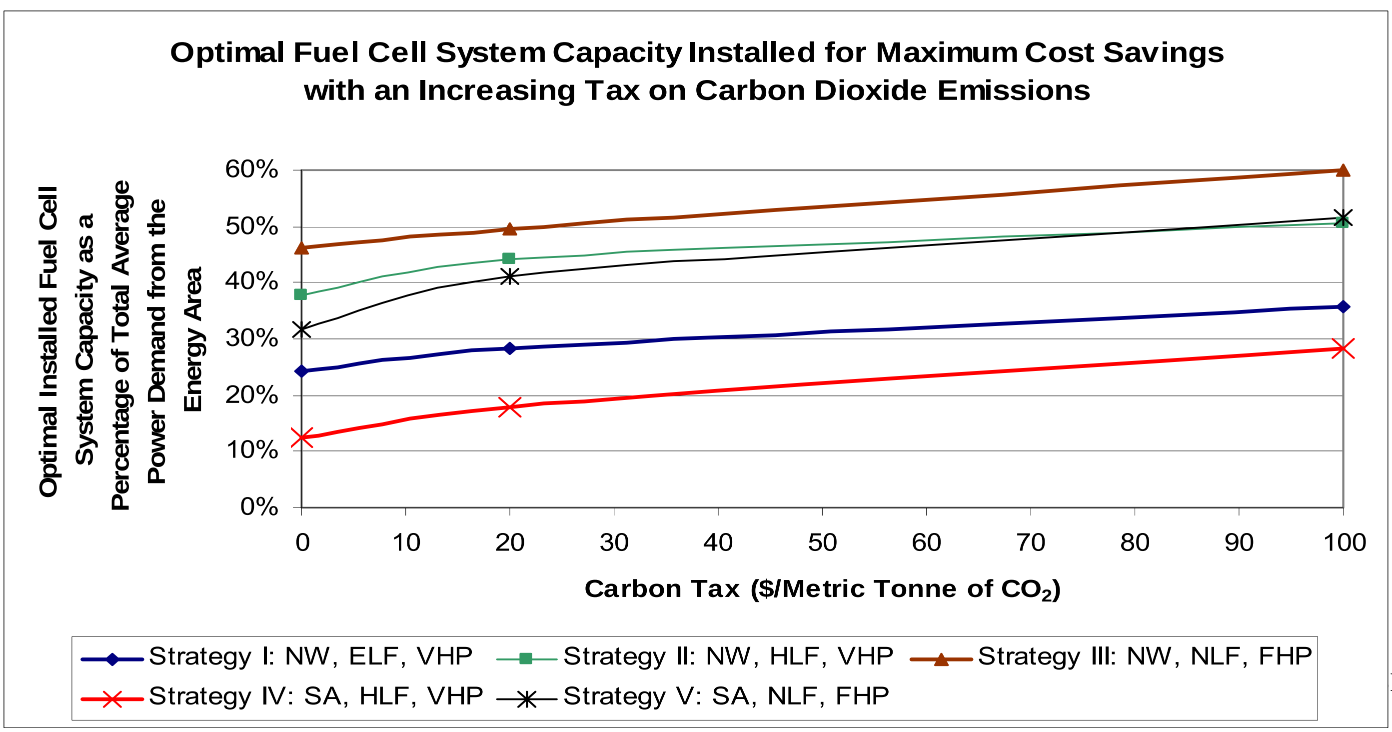


Figure 7. Best strategies for sales revenue for fuel cell manufacturers



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(bottom line) to Strategy III (top line), policy makers can increase the number of FCS installations from 13% to 46%, with no additional subsidy. Dollar-for-dollar, policy makers may find they can have the largest impact on FCS penetration by changing the way FCS are installed rather than by introducing a carbon tax.

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

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

Scenario E-1: Strategies for Maximizing Reductions in CO_2

Table 8 shows simulation results for the hypothetical scenario in which a carbon tax at \$1,000,000/tonne CO_2 is applied. The carbon tax is intentionally set to be unrealistically high so as to alter the function of the model. With an extremely high carbon tax, the model optimizes not for the highest financial savings, but rather for the highest reduction in CO_2 emissions. Setting the carbon tax at \$1,000,000/tonne CO_2 reveals the strategies with the lowest CO_2 emissions and the highest CO_2 emission reductions. The strategies that achieve the highest CO_2 emission savings are Strategies I, III, and V with reductions of 32%, 32%, and 37%, respectively.

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

Strategy II exhibits the highest installed capacity for fuel cell manufacturers, but the smallest reduction in CO_2 emissions. By contrast, Strategy III is not only one of the strategies with the lowest CO_2 emissions; based on the results in **Table 8**, it is also one of the strategies with the highest installed capacity, 85% of average power

Table 8. Best strategies for maximum CO_2 reductions

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

demand. Therefore, Strategy III appears to be one of the most economical for fuel cell manufacturers while also achieving some of the largest CO_2 reductions.

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

Of all scenarios, Strategy V achieves the highest reductions in CO_2 emissions. However, as shown in **Figure 6**, Strategy V is the second least economical for building owners. As shown in **Figure 7,** Strategy V is the third least economical for fuel cell manufacturers, except in a certain high carbon tax range. At a carbon tax of about $85 per tonne of CO_2 and higher, Strategy V becomes the second most economical strategy for fuel cell manufacturers. However, at an even higher carbon tax, Strategy V is again the third least economical for manufacturers.

Scenario E-2 – Building Types for Maximizing CO_2 Reductions

If FCSs are installed SA (not NW), Tables 11 and 12 show the best buildings for their installation for reducing CO_2 emissions, by building type and by the building name with the most similar load curve to that modeled. If Strategy IV is implemented, Table 9 shows that, of the 30 buildings investigated, FCSs could be installed in 26 of them and achieve reductions in CO_2 emissions. Of these, the building load curve with the greatest potential for CO_2 emission reductions is that load curve most similar to the Mudd Chemistry building, a wet laboratory. Buildings with such load curves can be expected to achieve a potential 32% reduction in CO_2 emissions (highlighted in yellow). This building load curve is also the most economical installation for fuel cell manufacturers (based on the 13 installations shown in Table 9) and for building owners (based on a previous run shown in Table 5). Wet laboratories appear to be one of the more effective building types for CO_2 and cost reductions. However, no particular building type stands out as being better than the rest in all cases for CO_2 emission reductions. This result underscores the importance of testing the FCS's performance against the particular load curves of the buildings they may serve, rather than generalizing by building type alone

If Strategy V is implemented, Table 10 shows that, of the 30 buildings investigated, FCSs could be installed in 26 of them and achieve reductions in CO_2 emissions. Of these, the building load curve with the greatest potential for CO_2 emission reductions is again that of the Mudd Chemistry building, a wet laboratory, with a potential 32% reduction in CO_2 emissions (highlighted in yellow). This building load curve is not the most economical installation for building owners (based on a previous run shown in Table 5), but it is one of the more economical installations. However, based on Table 10, the most economical installation for fuel cell manufacturers appears to be buildings with load curves most similar to the Center for Integrated Systems, another wet laboratory, highlighted in green with 12 installations.

Identification of Policy Options

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

- <u>Create incentives for FCS manufacturers to build systems with a VHP</u>

Strategies that implement FCSs with a VHP result in the highest financial savings in the costs of electricity and heat provision for building owners (Strategy I, in particular). The American FCS industry is composed of two major manufacturers that offer pre-commercial systems, FuelCell Energy Inc. and United Technologies Inc., neither of which offer systems with a VHP. As shown in this study, higher sales revenue for a FCS manufacturer is more highly correlated with a FHP, which they currently only offer. Although for them a VHP is an avant-garde design, the German fuel cell maker MTU does offer FCSs with a VHP as a feature. Policy makers could create incentives for American FCS manufacturers to offer this VHP feature as well.

- <u>Create partnerships between FCS makers and energy service companies (ESCO) to consolidate incentives towards higher energy cost savings</u>

The results showed a crucial difference between the strategy resulting in the highest sales revenue for fuel cell manufacturers (Strategy III) and the one with the highest energy cost savings for building owners (Strategy I). Furthermore, Strategy III is consistent with FCS manufacturers operating business-as-usual, designing their systems primarily as NLF with a FHP.

Strategy IV: Best Buildings for Highest CO_2 Emission Reductions

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

Table 9. Best building type load curves for maximum CO_2 reductions under Strategy IV

Strategy V: Best Buildings for Highest CO_2 Emission Reductions

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

Table 10. Best building type load curves for maximum CO_2 reductions under Strategy V

The results showed that a change away from the business-as-usual approach towards Strategy I would achieve not only higher energy and cost savings for building owners, but also higher CO_2 emission reductions.

To reconcile this dichotomy, policy makers can encourage FCS manufacturers to engage in financial partnerships with energy service companies (ESCO). Linking the financial incentives of FCS makers with ESCO has several benefits.

First of all, in such partnerships, the financial incentives of the FCS makers are linked with the downstream energy, cost, and emission savings of these systems. By partly owning and operating systems throughout their lifetime, FCS makers would be increasingly incentivized to build FCSs for maximum energy cost savings, since this objective would be aligned with their own profitability. For example, by forging such partnerships, it becomes in the manufacturer's interest to offer comprehensive and inexpensive O&M, to reduce initial FCS capital outlay costs, and to improve FCS reliability.

Second of all, FCS manufacturers bring a level of technical understanding of their systems that can reduce the perceived technical risk of investing in an installation and, consequently, reduce the project's cost of capital. With this lower interest rate, these FCS installation projects are more economical. By contrast, financial institutions are more likely to over or under-estimate the technical risk associated with new technology projects without a detailed understanding of the underlying devices. This tendency is a type of economic inefficiency that some have addressed in the recent years by hiring more technical experts.

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

Fourth, a major impediment to FCS installation projects has been the large initial capital cost to purchase systems. These large fixed costs ($1,000,000 or more per 200 kW system) exceed the typical annual budget ranges of facilities departments that operate buildings, a fact that reduces investment opportunities (Kulakowski 2006 & 2007). By contrast, partnerships between ESCOs and FCS makers can eliminate these large initial capital outlays by creating annual contracts base on amortized costs or based on per unit electricity and heating pricing.

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

- Facilitate installing systems within pre-existing thermal networks as retrofits

State and federal energy agencies could assist ESCO in locating pre-existing thermal networks within their regions. Many of these exist on university and on corporate campuses. For example, some excellent retrofit opportunities may exist within the University of California (UC), including UC Berkeley, which heats buildings with a steam heating network.

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

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

- Implement *MERESS* to identify specific state-owned buildings ideal for installation

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

4.0 CONCLUSIONS AND RECOMMENDATIONS

Building Types

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

- The electricity and heating load curves of individual buildings are extremely important in determining the economics and GHG emission reduction from an installation.
- These load curves are extremely important because the strategy that achieves the highest reductions in CO_2 emissions is with stand alone (SA) operation, in which one or a few FCSs manipulate their operation to meet the instantaneous electricity and heating demand from these buildings described by their load curves, without additional back-up or buffer of a surrounding electrical or thermal network.
- Specifically, at the highest incentive levels, the highest reductions in CO_2 emissions were observed with Strategy V, which incorporates stand alone (SA) operation, heat load following (HLF), and a fixed heat-to-power ratio (FHP).
- If one were to imagine this scenario, it would be analogous to cutting the electricity lines to one's house and powering it with the electricity from a stand-alone generator and its waste heat alone.
- For this stand alone strategy (Strategy V), Table 10 summarizes the best building type load curves for maximum CO_2 reductions. The top three of these load curves (Mudd, Braun, and Ginzton) are plotted in Figures 9 and 10.
- For this stand alone strategy (Strategy V), Table 5 shows the building load curves that achieve the most cost savings for building owners in procuring electricity and heat.
- For this stand alone strategy (Strategy V), the building load curve with the greatest reductions in CO_2 emissions is Mudd, a wet laboratory. Mudd is not the most economical building for installation, but it is one of the more economical buildings for installation, for both FCS manufacturers (as shown by the total number of installations) and building owners (as shown by their economic savings in Table 5.)
- Wet laboratories like Mudd are similar in their energy requirements to many industrial facilities, which also operate around-the-clock at high energy consumption levels. Wet laboratories appear to be one of the more effective building types for CO_2 and cost reductions. However, no particular building type stands out as being better than the rest in all cases for CO_2 emission reductions. This result underscores the importance of testing the FCS's performance against the particular load curves of the buildings they may serve, rather than generalizing by building type alone
- No particular building type (such as a wet laboratory or residence) stands out as maximizing any of these three goals consistently, across strategies: GHG emission reductions, cost savings to building owners, and high FCS manufacturer sales revenue.

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

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

Network Configurations

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

- Under Scenario D, with full government incentives and a \$100/tonne CO_2 tax, three different strategies achieve the highest GHG emission reductions, cost savings to building owners, and FCS manufacturer sales revenue:
- Strategy V achieves the highest reductions in CO_2 emissions.
- Strategy I provides energy for building owners with the lowest total cost, including the fixed and variable costs of resources and fuel over the investment time horizon.
- Strategy III provides the highest sales revenue for fuel cell manufacturers
- Strategy V achieves the highest reductions in CO_2 emissions. Strategy V incorporates stand alone (SA) operation, heat load following (HLF), and a fixed heat-to-power ratio (FHP) [SA, HLF, FHP]. It results in a maximum CO_2 emission reduction of 37% relative to a base case of no FCSs installed.
- Strategy I is most economical for building owners. Strategy I incorporates electrically and thermally networked (NW), electricity power load following (ELF), and VHP [NW, ELF, VHP]. The town's building owners gain the highest cost savings, 25% relative to a base case with no fuel cells and under full incentives and a \$100/tonne CO_2 tax. Figure 6 summarizes the best strategies for cost savings for building owners.
- Without any state and federal incentives or carbon tax, Strategy I is economical, although marginally so, with 3% cost savings, and a 29% reduction in CO_2 emissions. The significance of this finding is to demonstrate that just by changing the installation and operating strategy for FCSs, they can be installed economically, without any governmental incentives. FCSs have not typically been designed and installed to be connected to thermal networks, to follow electrical loads, and to achieve a VHP, either separately or in concert.
- Strategy III is most economical for fuel cell manufacturers. Strategy III is NW, NLF, with a fixed heat-to-power ratio (FHP) [NW, NLF, FHP]. Figure 7 summarizes the best strategies for high FCS manufacturer sales revenue.
- Strategy III results in 44 FCSs or 46% of average electrical power installed. However, this strategy results in an annual energy cost savings of only 3%. These simulations illustrate a striking dichotomy between the most economical strategy for building owners and the most economical strategy for fuel cell manufacturers. This dichotomy pervades most scenarios.
- Strategies III and V are consistent with the way that FCS manufacturers design their systems today, primarily as NLF with a FHP.
- By contrast, Strategy I is avant-garde for the fuel cell industry, in particular, in its use of a VHP.

- In all scenarios evaluated, higher energy cost savings are achieved with linking FCSs together in electrical and thermal networks, as opposed to installing them SA.
- When NW, combining either electrical or thermal load following with VHP improved economic performance.

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

Policy Recommendations

In the course of developing these conclusions, the article identifies four key policy options available for encouraging the design of distributed energy networks that reduce GHG emissions:

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

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

Furthermore, for the state and others to appreciate FCSs for their reductions in GHG emissions, the state needs to implement more precise GHG accounting procedures and inventory of historical emissions. One suggestion for improving the inventory is to critically evaluate the state's inventory. Another suggestion is to count FCSs consuming biogas (Staniforth 2000, Staniforth 2002, Bove 2005, Trogisch 2005) not as zero GHG contributors but as *net negative* contributors, because they convert each molecule of CH_4 that would be otherwise emitted into the atmosphere into a molecule of CO_2, which has 23 times less the global warming impact as CH_4 over a 100-year period.

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

Recommendations for Future Research

- The DOE's Hydrogen and Fuel Cell Program (http://www.hydrogen.energy.gov/) has historically focused almost entirely on implementing PEM fuel cells in cars. It has spent significantly less funding on developing stationary FCSs for electricity and heat provision for buildings. The Energy Commission could play a crucial role in closing this technology development gap by funding additional research and development of stationary FCSs.

- This study's results suggest the need to expand the fuel cell research paradigm from beyond device-level electrical efficiency and power density to optimizing FCSs within the context of their ultimate end-use environment. The article recommends further expansion of the *MERESS* model to include more permutations of FCS design and economics, and more building use data.
- Specifically, it would be helpful to expand the *MERESS* model to address the additional constraint of the second law of thermodynamics, which indicates that heat can only flow from hot to cold regions and not vice versa without external work applied. To address second law constraints, it would be helpful to have additional data on the temperatures at which heat is needed in buildings. Although load curves exist for the total quantity of heat demanded over time (kWh) for some individual buildings, very little data have been methodically compiled associating the quantity of heat demanded with the temperatures at which it is needed. Federal and state agencies would benefit from gathering data not only on the quantity of heat demanded over time, but also the temperatures at which it is demanded for industrial, commercial, and residential buildings.
- At the aggregate level, it would also be helpful to have more precise data on the quantity of heat demanded over time, in different sectors, and perhaps even by building. Although individual buildings may collect these data in some form (sporadically), state and federal agencies do not collect and compile these data from the multitude of demand sources. To appropriately track thermal demand over time and efficiency improvements in this area from implementing CHP FCSs, it would be extremely helpful for federal and state agencies to obtain measurements on and compile these data.

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 article 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.

Several benefits will be received from this work in the future:

- If policy makers, FCS manufacturers, and building owners implement the recommendations presented by the *MERESS* model, they could more effectively direct their technology investments and save millions of dollars in avoided government subsidies and misguided development efforts.

- Building owners can use their own unique electricity and heating demand curves and the simulation capability developed here with the *MERESS* model to evaluate the environmental and financial impact of installing a FCS in their own buildings. They can make more environmentally and financially informed decisions in this manner.
- The state could evaluate its own state-owned buildings to determine which of these state-owned buildings would allow for the greatest reductions in CO_2 emissions and costs with FCS installations.
- Implementing the *MERESS* model to design networks of CHP FCSs could result in extensive GHG emission reductions, even if these systems are fueled by natural gas (not just hydrogen). Installation of the systems would provide greater fuel efficiency, which results in less fuel consumption and lower GHG emissions.
- If applied, the *MERESS* model and these results can have a game-changing effect on the fuel cell industry.

Final Conclusions

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

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