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PART I OF II: DEVELOPMENT OF *MERESS* MODEL – DEVELOPING SYSTEM MODELS OF STATIONARY COMBINED HEAT AND POWER (CHP) FUEL CELL SYSTEMS (FCS) FOR REDUCED COSTS AND GREENHOUSE GAS (GHG) EMISSIONS

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ABSTRACT

Stationary combined heat and power (CHP) fuel cell systems (FCSs) can provide electricity and heat for buildings, and can reduce greenhouse gas (GHG) emissions significantly if they are configured with an appropriate installation and operating strategy. The Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*) is an optimization tool that was developed to allow users to evaluate avant-garde strategies for installing and operating CHP FCSs in buildings. These strategies include networking, load following, and the use of variable heat-to-power ratios, all of which commercial industry has typically overlooked. 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. It incorporates the pivotal choices that FCS manufacturers, building owners, emission regulators, competing generators, and policy makers make, and empowers them to evaluate the effect of their choices directly. *MERESS* directly evaluates trade-offs among three key goals: GHG reductions, energy cost savings for building owners, and high sales revenue for FCS manufacturers. *MERESS* 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. Part I of II articles discusses the motivation and key assumptions behind *MERESS* model development. Part II of II articles discusses run results from *MERESS* for a California town and makes recommendations for further FCS installments (Colella 2008 (a)).

KEYWORDS

Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*) optimization tool, fuel cell system (FCS), greenhouse gas emissions (GHG), carbon dioxide (CO2) 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

1.1. Introduction

Greenhouse gas (GHG) emissions and energy use could be reduced significantly through the use of stationary fuel cell systems (FCSs). Stationary FCSs are small scale power plants that can provide both electricity and useful heat directly to buildings with low emissions. Currently, U.S. electric power plants waste on average 68% of the available energy in their fuel, and boilers waste an additional 28% on average (Da Rosa 2003; EIA 1997). 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. For this reason, *MERESS* is a system-wide model of an entire energy network composed of FCSs and competing generator(s).

1.2. 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. FCSs can be installed and controlled using innovative designs, such as

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

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

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

1.3. 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 three 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 2.4 *Exploring Avant-Garde Designs for FCSs*. These five 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.

2.0 MOTIVATION

The primary energy problem addressed by the *MERESS* model is the design of novel networks of distributed CHP FCSs for reducing GHG emissions. The *MERESS* optimization tool was developed to allow users to evaluate different strategies for installing and operating distributed CHP FCSs in buildings. A unique aspect of the research is the analysis of FCSs in avant-garde design, installation and operating modes. For example, the *MERESS* model enables users to evaluate the benefits of networking systems. Almost all previous studies of FCSs assume that they operate in a *stand alone* mode, with a single FCS providing electricity and heat to a single building. By contrast, the *MERESS* model enables a user to analyze these systems as either stand-alone or networked. A networked FCS can send its electricity via a local low-voltage distribution grid to surrounding buildings (not just a single building) and can convey its heat to multiple buildings via a local district heating network, composed of water or steam pipes. The *MERESS* model enables users to quantify the degree to which networked operation affects GHG emissions and costs. The *MERESS* model is intended to help critically guide researchers developing fuel cells to make design trade-offs, engineers building FCSs to prioritize design goals, and governments addressing climate change to create appropriate GHG emission and energy legislation.

The *MERESS* model focuses on FCSs exclusively, and not other types of distributed generation, for several reasons. FCSs have the highest electrical efficiency and lowest emissions of all distributed generators. They are the only distributed generation technology that has met the strictest air pollution requirements. By contrast, microturbines fueled by natural gas have very low electrical efficiencies (around 20%) and higher air pollution emissions than FCSs. Similarly, internal combustion engines systems fueled by natural gas have relatively low electrical efficiencies (around 30%), higher air pollution emissions than FCSs, and noise abatement and maintenance concerns. For these reasons, *MERESS* model focuses entirely on FCSs, although it can be altered to evaluate other types of distributed generators.

2.1. Reduction in Energy Consumption and GHG Emissions

Stationary CHP FCSs can significantly reduce energy consumption and GHG emissions. Distributed CHP FCSs can be designed to be more efficient than conventional power if they are implemented in such a way that both their electricity and heat supply are consumed at high rates (or utilization levels) within the buildings they serve. By way of example, a distributed generator such as a CHP FCSs may produce 40 units of electrical power and 50 units of heat that can be recaptured for a building's space and hot water heating for every 100 units of fuel energy it consumes. Potentially, 90% of the energy in the fuel could be usefully directed. By contrast, a conventional power plant typically produces 32 units of electric power with 100 units of fuel energy and discards the 68 units of heat available (EPA 2002; Da Rosa 2003). In the US, conventional power plants do not typically recover heat for space and hot water heating due to the large distances between heat supply (in remote locations) and demand (in populated areas). On top of that, in conventional heat generation, additional fuel must be consumed in furnaces or boilers to produce heat for hot water and space heating. A typical furnace may produce 72 units of usable heat for every 100 units of fuel consumed, with 28 units wasted in the processes (EPA 2002; Da Rosa 2003). The potential energy savings from distributed CHP is approximately 1/6th of total energy needs in California, and approximately 1/5th of the total energy needs of the United States (Colella 2008 (b)). Distributed CHP FCS can reduce GHG emissions by 65% or more, compared with conventional generation (Colella 2008 (b).) Because of the high efficiency and low carbon use of the California grid, FCSs can reduce GHG compared with this grid only if they include CHP (Colella 2008 (b)). This statement is particularly the case for low temperature FCSs, such as proton exchange membrane fuel cell (PEMFC) systems or phosphoric acid fuel cell (PAFC) systems, which have lower electrical efficiencies than other FCSs, and therefore potentially higher carbon footprints than conventional grid unless their heat is effectively recovered (Colella 2008 (b)). Thus, by combining the production of electricity and heat, by being situated close to the sources of heat demand, and by recovering heat effectively, stationary CHP FCSs can significantly reduce fuel consumption and consequently GHG emissions. (An additional benefit of distributed power is greater security of uninterrupted electricity supply, in the event of a grid outage.)

2.2. Benefits of Detailed, Real-Time Simulations

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

Automakers evaluate their vehicles by testing them against driving cycles, records of desired vehicle speeds over time. **Figure 1** shows an example of a driving cycle from the U.S. Environmental Protection Agency (EPA) (EPA 2007). These driving cycle tests can be used to reveal information about the in-use vehicle performance, such as the engine efficiency, mileage, transmission efficiency, and emission profile. Engineers then use these results to improve vehicle design. Similarly, the *MERESS* model tests the performance and costs of distributed CHP FCSs against the electricity and heat load curves of towns and buildings to guide design improvements. **Figure 2** shows one example of such a load curve for a building, the electricity demand over every minute of a day for a residence (Advantica Ltd. 2003).

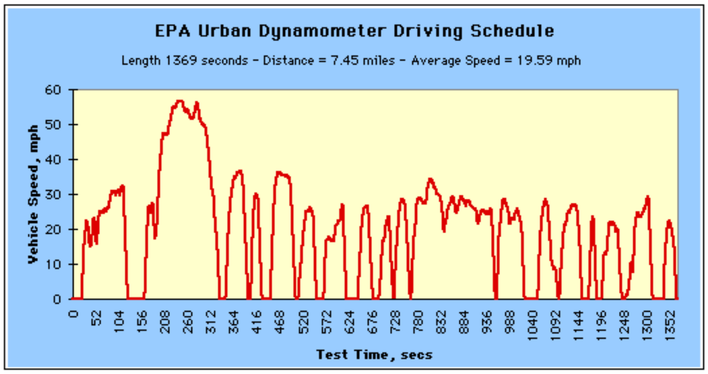

Figure 1: U.S. Urban Driving Cycle, a test of desired vehicle speed over time (EPA 2007)

The degree to which a fuel cell network genuinely achieves these GHG reductions depends on that particular network's in-use electrical and heat recovery efficiencies. In turn, these efficiencies depend on the design of the FCS network. A primary goal of the *MERESS* model is to use relatively inexpensive simulation studies to identify more financially and environmentally effective ways to design and install this FCS network.

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

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

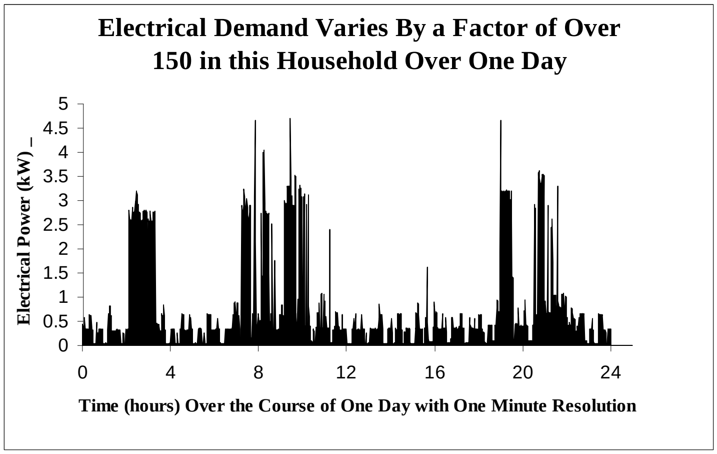

Figure 2: **Real-time electricity demand from a detached house the weekend of May 6, 1996. (Colella 2002(a)).**

Furthermore, certain types of FCSs with a particular range of heat-to-power ratios may serve a particular set of buildings more efficiently than others. For example, FuelCell Energy Inc.'s Molten Carbonate Fuel Cell (MCFC) system tends to operate with a heat-to-power ratio of one to two (Brdar et al. 2006). By contrast, United Technologies Inc.'s (UTC) PAFC systems tend to operate with a heat-to-power ratio of two to one (UTC Fuel Cells 2001; UTC Fuel Cells 2003.) Consequently, the MCFCs and the PAFCs may be best suited for installation in different buildings with different load curves and heat-to-power ratios. This example illustrates the importance of carefully analyzing an individual building's load curves and heat-to-power ratios over time. For this reason, the *MERESS* model incorporates detailed electricity and heating load curve data from 30 different buildings. These load curves capture different energy demand behavior over time.

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

2.3. Addressing Technical Barriers and Knowledge Gaps

Corporations have conducted their own evaluations of the economics of FCSs (Plug Power Inc. 2000; Arthur D. Little 1995; Behling 1999). However, these studies are likely to reflect the internal biases and vested financial interests of the corporations commissioning them. As a result, these studies must be reviewed critically. At the same time, it can be difficult to find experts with a detailed knowledge of the underlying technology's performance who are also unbiased and not financially incentivized to review a technology in either a positive or negative light. The bifurcation between unbiased technology evaluators and those with a detailed understanding of the technology's performance can lead to a significant market failure in innovation. This market failure may skew investments and research in either direction, either indicating too much or too little investment and research would be valuable. The asymmetry of information between investors and technologists can create a significant market failure in appropriate investments in technology and, subsequently, in commercialization of productivity-enhancing technologies. Such a market failure can lead to lower rates of economic growth.[1] This type of market failure can be attenuated with independently-funded, unbiased, and well-informed academics studies, such as the one conducted here.

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

Other academic studies of stationary FCSs concluded that their economics is heavily impacted by their capacity utilization (Thomas et al. 1999; Thomas et al. 2000). An individual power plant serving a single building can experience low capacity utilization, because demand for energy can vary significantly by time of day and season. For example, **Figure 2** illustrates that electrical demand in a typical British household varied by a factor of 156 during a single day in May (Advantica Ltd. 2003).

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

Other academic modeling studies have investigated the relative economics of installing and deploying one type of power plant compared with another (Lamont 1997, Lamont 2001, NREL 2004). However, these system-wide economic models have either not included FCS models or only included technically simplistic models of their operation, and have not investigated avant-garde operating strategies for FCSs.

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

Like Ballard Inc. and Bloom Energy Inc., many fuel cell developers have focused solely on building "electricity generating boxes." Their intention has been to then sell these boxes to customers who they hope will invent uses for them. This approach has not resulted in significant FCS market penetration, in part because many American utilities are only beginning to develop a core competency in distributed generation and in CHP. Utilities have not chosen this development route for several reasons. These reasons include, but are not limited to, traditionally low fuel prices in the U.S., legal restrictions, Not In My Back Yard (NIMBY) attitudes of residents toward traditional combustion power plants located close to their homes, and the higher air pollution-related health impacts from locating traditional power plants

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

closer to people. As a result of few such partnerships between utilities and FCS developers, FCS manufacturers have not cultivated an expert understanding of how to design, operate, and configure their FCSs to mitigate GHG, much less to analyze optimal operating strategies for them within networks. The *MERESS* model was developed to help forge this gap.

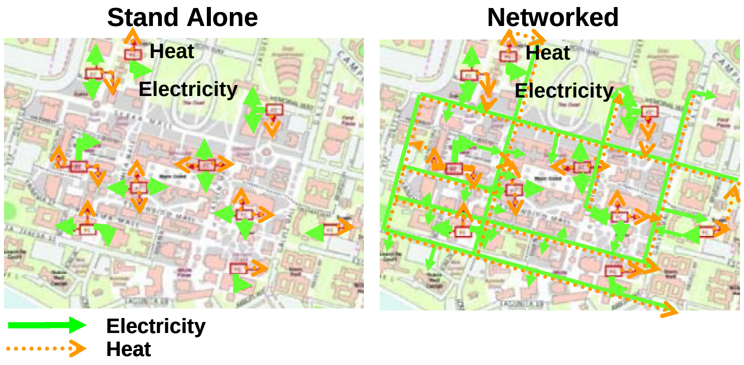


Figure 3. Comparison of SA and NW operating strategies

2.4. Exploring Avant-Garde Designs for FCSs

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

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

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

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

Networks are inter-connected energy distribution channels for conveying electricity or heat. If FCSs are SA, they cannot convey excess electricity or heat to other buildings. If SA, they can not convey excess electricity into low-voltage electricity distribution grids to send this excess to other buildings where additional electricity demand might exist. They also cannot convey excess heat into thermal networks of steam heating pipes to send unconsumed heat in one building to other buildings that may have a need for heat. **Figure 3** shows FCSs feeding electricity (dashed arrows) and heat (solid arrows) into multiple buildings in an energy consuming area, a town resembling a campus for a college, corporation, or government entity, referred to in these articles as Campustown. Campustown's building load curves are based on those from buildings on the Stanford University campus.

Figure 3 compares SA FCSs with NW ones. SA systems are defined here as not being able to convey either excess electricity into the low voltage electricity distribution grid or excess heat into a hot water or steam heating piping network to reach other buildings. While SA systems feed only nearby buildings, NW systems feed not only nearby buildings but also an entire energy network that serves dozens or hundreds of buildings. NW FCSs can convey their excess heat or electricity into electricity and heating distribution networks to reach other buildings. A primary benefit of operating FCSs as part of a network can be to increase the capacity utilization of each of the systems, an effect that can decrease the costs of the power plants. Distribution losses are typically close to 0% for electricity lines and around 8% for steam heating pipes across short distances in temperate climates (Murray 2007). The later depends primarily on the climate region and its outside temperatures.

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

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

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

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

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

Figure 4 compares three different FCS control strategies: HLF, ELF, and NLF. When a device is operated in a load-following manner, it produces only the amount of product demanded at that instant in time. The left side of **Figure 4** shows a FCS operating in a HLF manner; its output is primarily determined by the instantaneous heat demand of the building it serves. Its electricity is a by-product. **Figure 4** compares this control option with ELF, shown in the figure's center, in which the system's instantaneous electrical supply matches the instantaneous electrical demand of the building. The heat supply of the system is a by-product of the electrical supply.

FCSs may include some electrical energy storage within their systems to enhance their ability to rapidly respond to changes in electrical load. For the NLF control option, the FCS produces a fixed quantity of electricity and heat over time, which does not vary with the amount of electricity and heat demanded by the building.

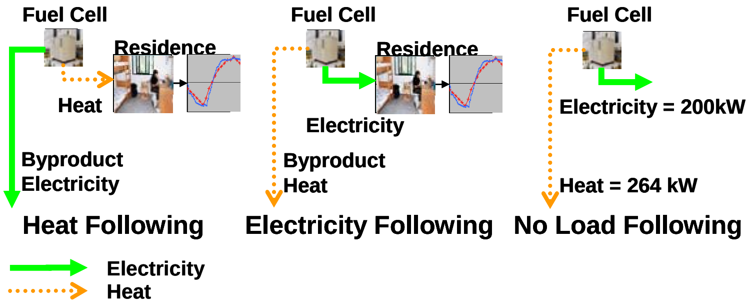


Figure 4. Comparison of load following operating strategies

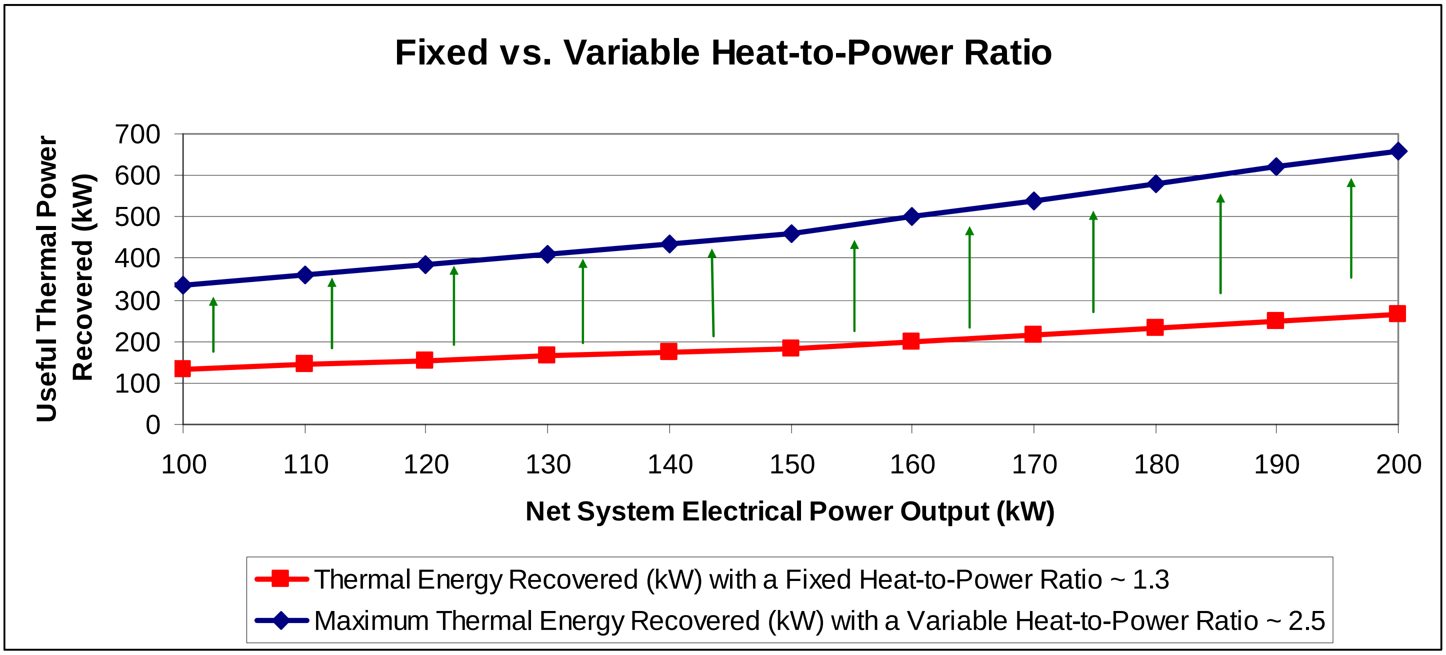
2.4.3. Variable Heat-to-Power Ratio (VHP) or Fixed Heat-to-Power Ratio (FHP)

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

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

Figure 5 compares and contrasts a FHP operating regime with a VHP. The data are based on the performance of a United Technologies Inc. 200 kWe PAFC System (UTC Fuel Cells 2001; UTC Fuel Cells 2003). Although this system is not currently designed to incorporate a VHP, it could be modified to do so, as explained in more detail in the next section. Between 100 and 200 kWe, the system normally has an approximately FHP of 1.3. This constant heat-to-power ratio is shown by the bottom line plotted and the linear slope over this range. The top most line plotted shows that the operating region could be extended, up to a maximum heat-to-power ratio of 2.5, for example. Under a VHP operating strategy, the heat-to-power ratio could range from anywhere between 1.3 and 2.5 (the area of the figure bounded by the top and bottom lines and populated by arrows). In this way, a VHP extends a system's operating range. If systems are designed with a VHP, their heat to power ratio can be changed to accommodate changes in heat and power demand. This change in heat and power supplied is achieved by changing the way the system operates internally. This can be done by either "pulling a lever" or through another feedback loop, as explained next.

Figure 5. Comparison of fixed vs. variable heat-to-power operating strategies



2.4.4. Methods to Achieve a Rapidly VHP

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

Colella (2002(b)). The reader can think of a FCS as being able to achieve a VHP by operating some of its pre-existing equipment as an auxiliary boiler or furnace.

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

3.0 MODEL DEVELOPMENT: OPTIMIZATION TOOL *MERESS*

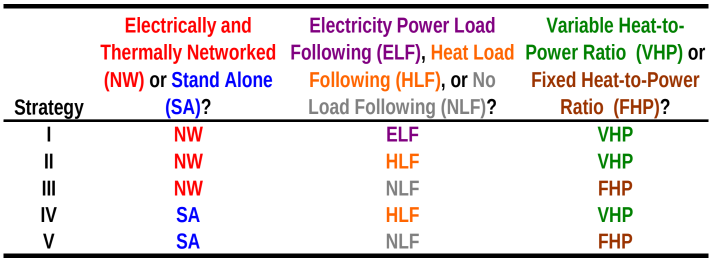
An optimization tool, *MERESS*, was developed to help users identify FCS configurations with the greatest reductions in GHG emissions and the highest financial savings. *MERESS* allows a user to optimize the configuration of CHP FCSs in supplying heat and electricity to buildings for maximum financial savings and maximum reductions in GHG emissions. *MERESS* allows a user to evaluate the electricity and heat supply from FCSs in different configurations against competing generators and against the electricity and heat demand from buildings. *MERESS* can be used to evaluate the feasibility of FCSs in any location, given specific information about the buildings in that location, for any set of building load curves, and by any building owner, community, FCS operator, or energy service provider. (In the subsequent Part II article, *MERESS* is applied to optimize the configuration of FCSs for a hypothetical town resembling a campus for a college, corporation, or government entity, called Campustown. (Colella 2008 (a)))

3.1. Installation and Operating Strategies Modelled

Three sets of avant-garde FCS design options are explained in the sub-section 2.4 *Exploring Avant-Garde Designs for FCSs*. The 3 sets of design options can be combined into 12 different installation and operating strategies. Of these 12 possible strategies, 5 of these are incorporated into the *MERESS* model. These 5 strategies are tested against a base case in which no FCSs are installed, and heat and power are provided exclusively by a competing generator or set of competing generators defined by the *MERESS* model's user:

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

Table 1 summarizes these operating strategies. The model is designed to investigate these five strategies because they are unique, and potentially game-changing. Fuel cell manufacturers have not typically designed these features (such as VHP) and these control strategies (such as HLF) into their commercially-available systems. They also typically have not installed systems to be both thermally and electrically NW. Most manufacturers build and install their systems to be SA, NLF, with a FHP, or according to Strategy V above. In this way, Strategy V acts as a benchmark of status quo designs against which to compare the performance of other strategies.



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

3.2. Model Capabilities

Given a certain installation strategy (I through V), *MERESS* finds the optimal capacity installation of FCSs to achieve the highest financial savings for the town of Campustown given a desired GHG emission tax rate and the particular electricity and heating demand characteristics of the town's buildings. *MERESS* also identifies strategies that maximize reductions in CO_2 emissions, for a given set of user specified inputs. Users can find strategies for maximizing CO_2

emission reductions by deploying *MERESS* with an extremely high, unrealistic carbon tax. For scenarios in which FCSs operate SA (Strategies IV and V), *MERESS* also finds the most economical buildings for installation, and the particular buildings that will achieve the highest reductions in CO_2 emissions.

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

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

3.3. Optimization Function

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

$$S = C_A - C_B,$$

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

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

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

3.4. Input Data

3.4.1. Electricity and Heating Demand Load Curves for Buildings

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

The building demand data included in *MERESS* is based on the measured electricity and heating demand curve data for buildings on the Stanford campus. Stanford building demand data are available for free, for a large number of buildings, at precise time increments (one hour), over the course of one year. All 300+ campus buildings are simulated based on a representative sample of 30 buildings. According to statistical guidelines, an underlying population can be reasonably represented by a sample population of 30 or more (Devore 1995). (As a general rule of thumb, if the sample size is greater than 30, the standard deviation of the sample can be replaced with that of the underlying population, and the mean of the sample is consistently within rounding of the population mean.) The sample population of 30 buildings is composed of five different building types. These five building types generally can represent all of the buildings on the entire campus. The measured data for electricity and heat demand from the sample population of 30 buildings are scaled up in proportion to the building's representation in the energy area, to represent electricity and heating demand throughout the entire town. Yearly data are simulated by using four sample weeks of measured data, from each of the four seasons, to include the effect of seasonal variations. **Figures 6** and **7** show examples of some of the sample input data for building load curves for one week during winter from five buildings of five different types, for electricity and heating demand, respectively.

The five main types of buildings investigated were offices/classrooms, museums/libraries, residences, wet laboratories, and dry laboratories. Wet laboratories are buildings designed to handle multiple experimental set-ups involving chemicals, drugs, biological matter, and/or electronics, which require specialized piped utilities, direct ventilation, exhaust fume extractors, workbenches designed for noxious fumes, dust control, and/or temperature-and humidity-sensitive heating, ventilating, and air-conditioning (HVAC) systems. They include biology and chemistry labs. By contrast, dry laboratories are buildings that primarily handle materials, electronic equipment, or large instruments that require a dry environment. They may require specialized equipment such as high performance HVAC, exhaust fume extractors, vibration control, and/or dust control. Examples include computing facilities, robotics labs, and clean rooms. In this way, electricity demand (DE) and heating demand (DH) are simulated for each building in Campustown at every hour over the course of one year. (The available thermal building demand data did not include the temperatures at which heat was demanded; as a result, an analysis of second law constraints was beyond the scope of this analysis.)

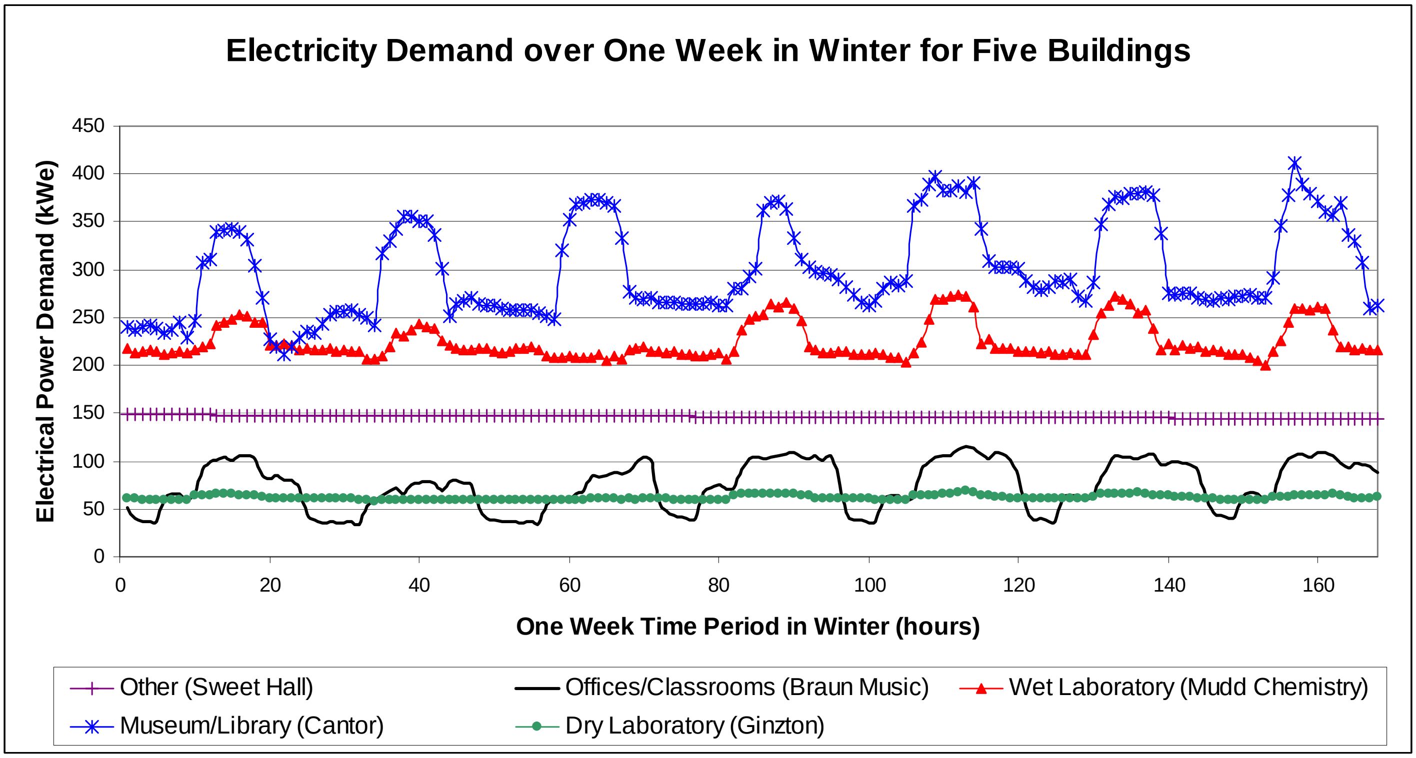


Figure 6. Sample measured input data for building load curves showing electricity demand from five different building types over one representative week during winter

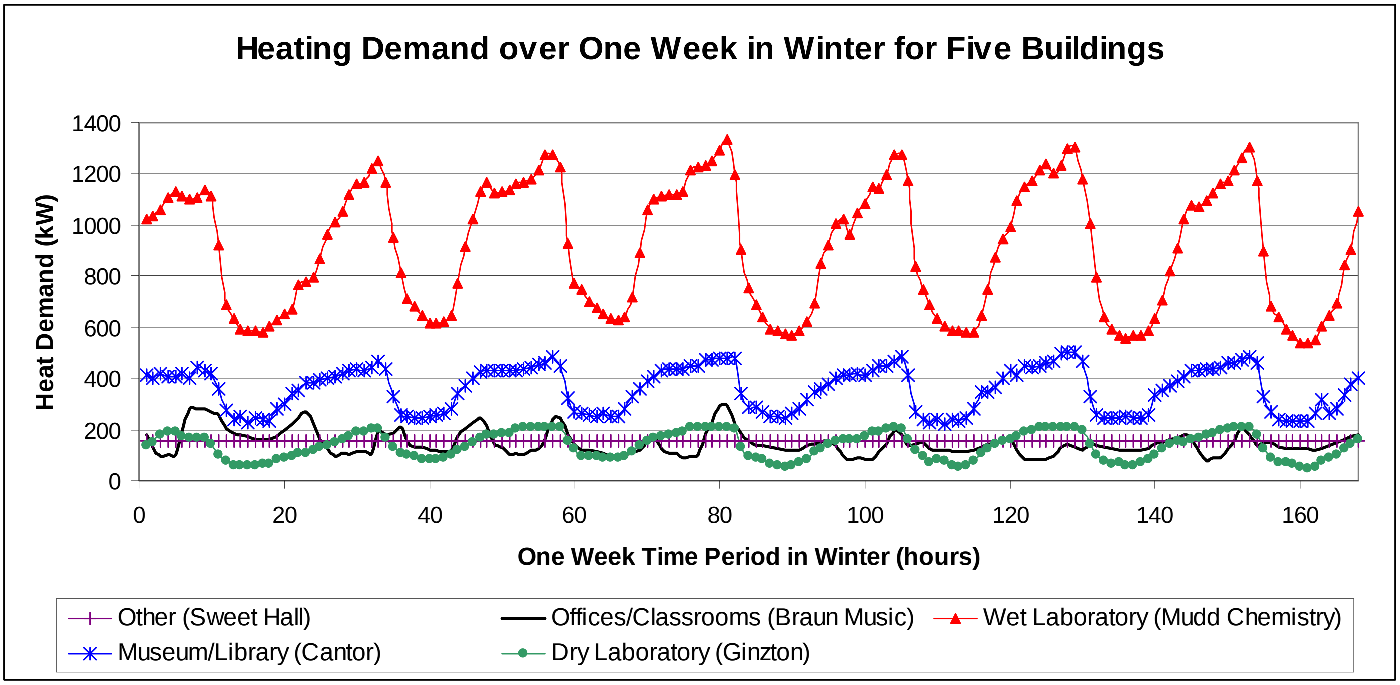


Figure 7. Sample measured input data for building load curves showing heating demand from five different building types over one representative week during winter

3.4.2. FCS Operating Data

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

The FCS operating data included in *MERESS* is based on a PAFC system by United Technologies Inc., named the PureCell. The PureCell has a maximum electrical output of 200 kWe and maximum thermal output of 264 kW of heat, under normal operating conditions (UTC Fuel Cells 2001; UTC Fuel Cells 2003). *MERESS* models a PAFC system instead of another fuel cell type because these systems, more than other fuel cell types, depend on thermal networking and effective heat recovery is to operate in an environmentally benign manner: lower temperature systems (such as PAFC and PEMFC) have lower electrical efficiencies and, as a result, can only achieve reductions in GHG emissions through CHP and effective heat recovery (Colella et. al. 2008). The PureCell was also chosen for the *MERESS* model over other fuel cell systems because it is one of the only commercially sold stationary FCSs operating on natural gas, its operating and financial data are publicly available, and this system has been technically proven over a 20+ year period during which time 300+ operating prototypes and semi-commercial systems have been deployed throughout the world. Also, in contrast to other fuel cell types and systems, the PureCell has been engineered to quickly change its electrical output in response to changes in electrical demand. No other American-made FCS has been tested in the field for as long a period of time with as long fuel cell stack lifetimes as the PureCell. For example, the other major U.S. stationary FCS manufacturer, FuelCell Energy, sells a stationary MCFC system that has a stack lifetime approaching five years and a balance of plant lifetime of about 20 years. Two other companies, Bloom Energy (formerly Ion America) and Siemens-Westinghouse, are developing stationary SOFC systems, but they have sold few units, and they do not disclose their FCS's operating and financial data to the public. However, *MERESS* can be easily altered to include the operating data of other fuel cell manufacturers.

MERESS models the PureCell between an electrical operating range of 100 to 200 kWe. Under conventional operating conditions, over this range, the PureCell has a FHP of about 1.3, as shown in **Figure 5**, and, consequently, a constant net system electrical efficiency and constant heat recovery efficiency. However, *MERESS* enables the system to be modeled under unconventional operating conditions, in which it can achieve a VHP, and can vary its effective electrical and heat recovery efficiencies. *MERESS* allows the user to specify a representative heat-to-power ratio range.

For the results presented in the subsequent *Part II* article, **Table 2** shows a set of representative operating data for the FCSs modeled in *MERESS* (Colella 2008 (a)). The system operates with a net electrical efficiency of 37%, a heat recovery efficiency of 48%, for a combined electrical and thermal (overall) efficiency of 85% (37% + 48% = 85%). These efficiencies are representative for PAFC. They are based on efficiency data from the only U.S. commercial supplier of stationary PAFC, United Technologies Inc. (UTC Fuel Cells 2001; UTC Fuel Cells 2003). *MERESS* allows the system to be operated outside of these conditions, with an intentionally lower electrical efficiency, under VHP strategies. With a VHP, the system is sometimes intentionally operated with a lower net system electrical efficiency, so as to supply additional heat that is demanded. *MERESS* can explore the heat-to-power ratio over a full spectrum of part-load operations. For example, for the results presented here, the heat-to-power ratio range is chosen to range from 1.3 to 2.5 in these variable heat-to-power scenarios. A maximum heat-to-power ratio of 2.5 for a 200 kWe system translates to a maximum thermal output of 500 kW per system. For these scenarios, *MERESS* assumes the efficiency of this marginal heating is 90%. Users can conduct sensitivity analyses with *MERESS* to investigate how their results change if the FCSs have different electrical and heat recovery efficiencies.

As shown in **Table 2**, the user can model a FCS by choosing several variables in *MERESS*. For example, the user can define both the electrical and heat recovery efficiencies of the system, over a specified operating range. The user can vary the range of minimum and maximum electrical output associated with these efficiency values. Efficiencies can be entered as point values over this operating range. According to the stationary FCS manufacturing data made available to the authors, all of these systems sold in the U.S. exhibit an essentially constant electrical efficiency over their recommended operating range. As a result, to remain consistent with these data, the authors chose to model FCS efficiencies as point values for FHP strategies.

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

Table 2. Model input data for FCS operation

There may be some confusion here because an individual fuel cell (without the surrounding balance of plant for fuel and oxidant delivery, etc.) exhibits an electrical efficiency that declines as the electric power output increases, often depicted by a polarization curve. By contrast, a fuel cell system does not exhibit this characteristic. This point has been greatly misunderstood even within the fuel cell industry and even by researchers making policy recommendations about fuel cells. For an illustration of this point, please see O'Hayre et al., Chapter 10, Figure 7.4, p. 287 (2006), which compares a typical fuel cell/fuel cell stack polarization curve with the electrical efficiency curve of a fuel cell sub-system. Based on the data available for stationary fuel cell systems, the authors determined it would be accurate to model the fuel cell systems' electrical efficiency as a point value over their recommended operating range for FHP strategies. (As a result of this choice in model design, it is possible to apply the model to other types of distributed generators other than FCSs.)

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

MERESS considers first law constraints (conservation of energy), but not second law constraints (direction of heat flow from hot to cold) directly in detail. With the UTC systems, the heat recovery temperatures are high enough that most building applications can be met. For example, previous studies by Colella (2003 (b)) showed that even lower temperature PEMFC could supply all of their waste heat as recoverable heat to buildings, so long as pinch point analysis and careful heat exchanger design are employed. Since the PAFC operate at higher temperatures than PEMFC (200°C compared with 80°C), the buildings analyzed in this study can recover their heat more easily. (Also, a more detailed analysis including second law constraints was beyond the scope of this work because building heating demand data indicating temperatures at which heat is demanded were not readily available.)

3.4.3. FCS Financial Data

MERESS calculates the total yearly fixed costs of the FCSs from the capital, installation, maintenance, and other costs. **Table 3** shows a *MERESS* table of data inputs for these costs (second column) based on the PureCell (Menar 2003; Coletto 2007). The third column lists the annuity payment equivalent of this fixed cost in the second column, assuming a FCS lifetime of 10 years (in the field, they have lasted 20 years), and based on the annuity formula:

$$A = Pr/(1-1/(1+r)\hat{}n),$$

where A is the value of the annuity, P is the principle (the amount borrowed or credited at time t=0), r is the cost of capital, and n is number of years (10 years) over which the annualized payments are made (Ross et al. 2007; Brealey et al.

2007). Educational institutions may have access to a very low cost of capital, because these institutions can often borrow at the bond rate for educational projects (Canellos 2003). In this example, r =7.42% to reflect the relatively low borrowing rates that educational institutions access, close to the risk-free rate or government bond rate. (The bond rate was 4.91% on a 30 year bond on Oct. 15th 2007 (U.S. Department of the Treasury 2007)). The sum of these annuity payments in the third column is shown in the total yearly fixed costs of the FCS, shown in the last row ($138,368 in this example). The capital costs ($950,000) are for a single 200 kWe system. The installation costs ($ 250,000) assume ground-level installation, close to utility tie-in lines (such as the natural gas line, city water, and the electricity distribution grid), and close to the building for thermal tie in to the building. The installation and commissioning is turn-key, and includes site design and engineering, all required permits (utility, construction, city, air permits, etc.), and all material and labor. The shipping cost ($20,000) assumes the cost of shipping the system from the manufacturing site in Connecticut to California, where the systems may be assumed to be installed. The premium full service contract covers maintenance and repair for 10 years. It is an annual payment of approximately $60,000 for 10 years. It includes preventative maintenance and repairs (labor and parts), scheduled and un-scheduled maintenance, 24/7 remote monitoring, next-day business response to unplanned events, and includes an extended warranty for replacement costs of the major fuel cell components.

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

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

3.4.4. Government Incentives

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

3.4.5. Carbon Tax

The Intergovernmental Panel on Climate Change (IPCC) evaluates the global warming mitigation cost of CO_2 over a range of between $20 and $100/tonne CO_2 (Working Group III

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

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

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

Table 3. Model input data for FCS costs

IPCC 2007). The *MERESS* model allows users to evaluate a carbon tax over the same range. The carbon tax increases the natural gas price seen by the FCSs. It also increases the electricity and heating price of the competing generator.[4]

For the results presented in the subsequent *Part II* article, the carbon tax was assumed to have the same effect on increasing electricity and steam heating prices of the competing generator that a market-related increase in fuel price might have (Colella 2008 (a)). In the model, the tax increases the price of electricity and the price of steam in proportion to the relative fuel consumption associated with each. This approach is an accepted marginal cost accounting method (Atkinson et al. 2006). This method is also chosen because it most closely reflects the use of carbon within the energy system, and, therefore, is the most appropriate set of assumptions for the minimization of CO_2 calculations that the model can perform.

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

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

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

The effect of a carbon tax increasing is analogous to the effect of fuel prices increasing in many cases. A user can change the same input parameters in the *MERESS* model not only to evaluate an increase in carbon tax, but also to evaluate an increase in fuel prices. Users can use *MERESS* to evaluate the effect of fuel costs trending upward, as projections from the

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

U.S. Department of Energy's (DOE) Energy Information Administration (EIA) or the CEC might suggest.

3.4.6. Competing Generator Data

The *MERESS* model tests the 5 strategies against a base case in which no FCSs are installed, and heat and power are provided exclusively by a competing generator or set of competing generators defined by the *MERESS* model's user. *MERESS* allows the user to specify the competing generator's financial and operational characteristics. The competing generator is assumed to be available to provide electricity or heat not provided by the FCSs. It can sell excess electricity over the high-voltage transmission grid. In this way, the competing generator reflects the financial situation encountered by many corporate and university campuses that chose to buy power from a nearby cogeneration plant, or another source. Incorporating competing generator data into the model in this way also allows some modeling of emergent competitive behavior; in response to changes in competitor behavior (efficiency, prices, allocation of taxes, etc.), the best strategies (from Strategies I through V and more) for building owners to implement for maximizing carbon emission reductions and economics will change (Axelrod 1997.) *MERESS* is equally capable of modeling retrofits as it is of modeling new installations, simply by accounting for the difference in costs in these two approaches, which the user can input. *MERESS* models the financial decisions from the point-of-view of the town. It does not model the financial decisions that the competing generator's owner makes directly. As the FCSs displace competing generator capacity, the competing generator is free to sell this displaced power into the grid. However, these decisions of the competing generator are not directly modeled in *MERESS*. *MERESS* models financial decisions from the viewpoint of the town. *MERESS* accurately model the choices that a town makes when it decides either 1) to buy electricity and heat from a dedicated competing generator, or 2) to install and operate a network of distributed FCSs. In making this choice, the town experiences neither energy nor demand charges. These charges are leveled by external utilities. The town only sees the capital and running costs of the FCS, and the competing generator's electricity and steam prices. The *MERESS* financial model represents this set of choices between two competing financial decisions accurately.

The competing generator operating data already included in *MERESS* are based on a high-performance CHP CCGT power plant, the same plant installed on the Stanford campus. This data is based on financial and efficiency data for the Stanford 50 megawatt (MW) cogenerative power plant, shown in **Table 4** (Stanford University Utilities Department 2007). The steam price above is \$0.056/kWh of steam (\$16.32/million BTU of steam) and the electricity price is \$0.085/kWh of electricity. These values are the estimated prices of steam and electricity at the University excluding the cost of the distribution networks. Specifically, in both cases, the cost of the distribution network is estimated from Utilities department data and subtracted from the price the University charges to its departments for steam and electricity, respectively. This adjustment enables apples-to-apples comparisons between the fuel cell and competing generator scenarios. (Another approach to make a fair comparison is to add the estimated cost of the distribution networks to the fuel cell scenarios.) Further details of this calculation are shown in Appendix A. As in the model, the Stanford cogeneration plant sells any unused electricity back to the grid. It typically sells half of its maximum electrical capacity (about 25 MW) over the grid under normal operation. Waste heat is associated with this electricity sold.

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

Table 4. Model input data for competing generators

3.4.7. Networking

Within the model, FCSs that are electrically networked can send their electricity to surrounding buildings via the local low-voltage electricity distribution grid, with no energy losses. Systems that are thermally networked can send their heat to surrounding buildings via steam heating pipes with a certain percentage heat loss. Scenarios modeled with non-networked systems do not include this downstream heat loss because steam is not conveyed over a network. *MERESS* assumes that the electricity and heating distribution lines are owned and were previously installed by the town, like many corporate and college campuses. (As a result, the model does not encode any legal interpretations of regulatory restrictions of electrically networking across public roads that could affect installations in other types of environments.)

The heat loss rate within the network that is already included in *MERESS* is 8%. This assumption reflects the measured data describing these networks on the Stanford campus, and many other university and corporate campuses in.

4.0 CONCLUSION

Part I of II articles describes the fundamental assumptions behind the Maximizing Emission Reductions and Economic Savings Simulator (*MERESS*) optimization tool. *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, 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. Part II of II articles 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 (Colella 2008 (a)).

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SPM2, p.12; Figure SPM 5B, p. 13; website: http://www.mnp.nl/ipcc/docs/FAR/ApprovedSPM0405rev4b.pdf.

APPENDIX A

The steam heating price of $0.056/kWh is derived as follows. The steam price has three major components: energy cost (65%), the combined distribution system and plant operations and maintenance (O&M) (20%), and debt from capital projects (15%). Mr. Dean Murray of the Stanford Utilities Department estimated that the portion of each of these associated with the steam power plant and not the steam pipe distribution network was 100%, 50%, and 25%, respectively (Murray 2006-2007). If one multiplies these numbers together (65%*1.00+20%*0.5+15%*0.25 = 78.75%), one can estimate that approximately 78.75% of the University's charged steam price is associated with the steam power plant and not the steam pipe distribution networks. The University's listed FY08 price for steam is $20.12 per 1,000lbs (Stanford University Utilities Department 2007). The steam heating price is then calculated as the product of 78.75% and University's listed price for steam, which equates to $0.056/kWh.

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