Economic and Environmental Optimization Models for Refining Fuel Cell Use

by

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Abstract

We developed energy system optimization models to identify new strategies for designing, installing, and controlling stationary cogenerative fuel cell systems (FCSs) so as to minimize 1) electricity and heating costs for building owners and 2) emissions of the primary greenhouse gas -- carbon dioxide (CO₂). A main goal of this work is to employ relatively inexpensive simulation studies to discover more financially and environmentally effective approaches for installing FCSs. Models quantify the impact of different choices made by power generation operators, FCS manufacturers, building owners, and governments with respect to two primary goals -- energy cost savings for building owners and CO₂ emission reductions. These types of energy system models are crucial for identifying cost and CO₂ optima for particular installations because optimal strategies change with varying economic and environmental conditions, FCS performance, the characteristics of building demand for electricity and heat, and many other factors. Models evaluate both “business-as-usual” and novel FCS operating strategies. For the scenarios examined here, relative to a base case of no FCSs installed, models indicate that novel strategies could reduce building energy costs by 25% and CO₂ emissions by 80%.

1. Introduction

The U.S. wastes 1/5th of its total energy consumption, 21 Quadrillion British Thermal Units (Quads), as heat at power plants, and then re-generates approximately this same amount downstream to heat buildings and industry, as shown in the U.S. energy flow chart in Figure 1. If traditional, centralized electric power production were replaced with high-efficiency, low emission, decentralized, cogenerative power plants, the U.S. could reduce its energy consumption by up to 1/5th. While the average U.S. electric power plant operates with an efficiency of about 32%, distributed generators achieve efficiencies as high as 90% (combined electrical and thermal.) These distributed generators can be located close to buildings so that their heat can be recovered for building space and hot water heating. By contrast, centralized generation it typically located far from population centers, not close to sources of thermal demand. One type of high-efficiency, low emission distributed generator is the stationary cogenerative (or or combined heat-and-power (CHP)) fuel cell system.

Of all distributed generators, this paper focuses on fuel cell systems for several reasons. Fuel cell systems have a higher electrical efficiency, lower greenhouse gas emissions (carbon dioxide (CO₂), methane (CH₄), etc.), and lower air pollutant emissions (sulfur oxides (SOₓ), nitrogen oxides (NOₓ), carbon monoxide (CO), particular mater (PM), etc.) than all other types of distributed generators consuming the same fuels. By contrast, microturbines fueled by natural gas have very low electrical efficiencies (around 20%) and higher air pollution emissions than fuel cell systems fueled by the same fuel. Similarly, internal combustion engines systems fueled

1 Figure courtesy of Gene Berry, Lawrence Livermore National Laboratory (LLNL), Livermore, CA.
Figure 1

1 Quad = Quadrillion BTUs = $10^{15}$ BTU = 1.0551 Exajoules = 1.0551 $10^{18}$ Joules
by natural gas have a relatively low electrical efficiency (around 30%), higher air pollution emissions than fuel cell systems, as well as noise abatement and maintenance concerns.

Stationary fuel cell systems (FCS) can provide heat and power to buildings with lower greenhouse gas emissions than other approaches, especially if they are optimally configured to ensure that their instantaneous electricity and heat supply is always consumed. Figure 2 compares and contrasts CO₂ emissions from different types of power plants and heat generators, for the same total quantity of electricity and heat produced. Cogenerative fuel cell systems fueled by natural gas can create 1/3rd the CO₂ as conventional systems, if they are designed to recover heat with high end-use electricity and heat capacity utilizations. They release no net CO₂ emissions if they are fueled by renewable hydrogen (H₂).

![Table](image)

<table>
<thead>
<tr>
<th>Source of Electricity or Heat</th>
<th>CO₂ Emission Factor (g/kWh_e or g/kWh_heat)</th>
<th>Electricity Production (MWhr)</th>
<th>Heat Production (MWhr)</th>
<th>CO₂ Emissions (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: Conventional System</td>
<td>Coal Power Plant with Steam Turbine</td>
<td>860</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Coal Fired Boiler / Furnace</td>
<td>410</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Case 2: Average System</td>
<td>Mix of 1999 US Electric Generation Plant</td>
<td>600</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Boiler / Furnace (72% efficient)</td>
<td>280</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Case 3: Advanced System</td>
<td>Cogenerative Combined Cycle Gas Turbine</td>
<td>380</td>
<td>2</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Boiler / Furnace (92% efficient)</td>
<td>219</td>
<td>0</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Case 4: Fuel Cell System fueled by natural gas</td>
<td>Cogenerative Molten Carbonate Fuel Cell</td>
<td>373</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Case 5: Fuel Cell System fueled by renewable hydrogen</td>
<td>Cogenerative Molten Carbonate Fuel Cell</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

2. Methods

Our energy system optimization models evaluate novel FCS operating strategies, not typically pursued by commercial industry. Most FCS today are installed according to a “business-as-usual” approach: 1) stand-alone (unconnected to district heating networks and low-voltage electricity distribution lines), 2) not load following (not producing output equivalent to the instantaneous electrical or thermal demand of surrounding buildings), 3) employing a fixed heat-to-power ratio (producing heat and electricity in a constant ratio to each other), and 4) producing only electricity and no recoverable heat. By contrast, our models consider novel approaches as well. Novel approaches include 1) networking (connecting FCSs to electrical and/or thermal networks), 2) load following (having FCSs produce only the instantaneous electricity or heat demanded by surrounding buildings), 3) employing a variable heat-to-power ratio (such that FCS can vary the ratio of heat and electricity they produce), 4) co-generation (combining the production of electricity and recoverable heat), 5) permutations of these together, and 6) permutations of these combined with more “business-as-usual” approaches.

3. Results

We discuss model results for a California town, and, generalizes these results for a diverse audience. Model results show that the most optimal strategies for cost and CO₂ savings differ, but both invoke novel approaches. The strategy with the highest cost savings combines cogeneration, networking, variable heat-to-power ratio, no load following for the primary control at maximum electrical output, and subsequent heat load following for the secondary control. Results assume a base case with no FCSs installed and most power and heat provided by a
cogenerative combined cycle gas turbine and any additional electricity supplied by the average mix of power plants in California. Relative to the base case, this strategy results in an approximate 25% cost reduction. Similarly, the strategy with the highest CO₂ emission savings combines cogeneration, networking, variable heat-to-power ratio, heat load following for the primary control, and subsequent no load following for the secondary control. Relative to the base case, this strategy results in CO₂ savings of 80%. Model results indicate that energy cost savings and CO₂ reductions are highest with permutations that simultaneously invoke a combination of “business-as-usual” and novel approaches.

Energy costs and CO₂ emissions can be reduced significantly by switching from certain “business-as-usual” approaches to novel ones; specifically from 1) stand-alone to networked, and then from 2) fixed heat-to-power ratio to variable. Switching from a “business-as-usual” approach to a novel one can improve energy cost savings more than retaining a “business-as-usual” approach and increasing the carbon tax from $0 to $100/metric tonnes of CO₂. A carbon tax can provide more cost savings when combined with novel approaches rather than with “business-as-usual” ones.

Cost optima are most sensitive to 1) the FCS maximum electrical output, 2) the FCS electrical efficiency, and 3) the natural gas, steam, and electricity prices. CO₂ optima are most sensitive to 1) FCS electrical efficiency, 2) the maximum heat-to-power ratio, and 3) FCS heat recovery efficiency. For the strategies optimized for cost or CO₂, the electrical and thermal capacity utilizations of the FCSs approach 100%.

4. Conclusions
For California town examined here, relative to a base case of no fuel cell systems installed, energy system optimization models indicate that novel operating strategies for these fuel cell systems could reduce building energy costs by 25% and CO₂ emissions by 80%. Model results indicate that energy cost savings and CO₂ reductions are highest with permutations that simultaneously invoke a combination of “business-as-usual” and novel strategies. We conclude that energy costs and CO₂ emissions can be reduced significantly by switching from certain “business-as-usual” approaches to novel ones in the way that stationary fuel cell systems are designed, controlled, installed, and operated.

5. References


