Dynamic modeling and evaluation of solid oxide fuel cell – combined heat and power system operating strategies

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ABSTRACT

Operating strategies of solid oxide fuel cell (SOFC) combined heat and power (CHP) systems are developed and evaluated from a utility, and end-user perspective using a fully integrated SOFC-CHP system dynamic model that resolves the physical states, thermal integration and overall efficiency of the system. The model can be modified for any SOFC-CHP system, but the present analysis is applied to a hotel in southern California based on measured electric and heating loads. Analysis indicates that combined heat and power systems can be operated to benefit both the end-users and the utility, providing more efficient electric generation as well as grid ancillary services, namely dispatchable urban power.

Design and operating strategies considered in the paper include optimal sizing of the fuel cell, thermal energy storage to dispatch heat, and operating the fuel cell to provide flexible grid power. Analysis results indicate that with a 13.1% average increase in price-of-electricity (POE), the system can provide the grid with a 50% operating range of dispatchable urban power at an overall thermal efficiency of 80%. This grid-support operating mode increases the operational flexibility of the SOFC-CHP system, which may make the technology an important utility asset for accommodating the increased penetration of intermittent renewable power.

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1. Introduction

The current United States energy infrastructure provides affordable and reliable electricity. However, the current energy infrastructure is dependent upon the combustion of fossil fuels, which are limited energy resources that effectively store large amounts of carbon apart from the atmosphere. To alleviate our dependence on fossil fuels, the United States has two major research and development strategies that are relevant to this paper: (1) increasing fossil fuel system efficiencies, and (2) increasing utilization of renewable energy resources. The development and deployment of alternative energy technologies is particularly challenging because the integration of energy technologies must continue to provide reliable, economical, and secure electricity to the public. For desired changes in energy to be effective, advances in grid infrastructure, electric rates, as well as grid connection and management strategies are required. The current U.S. energy system and market has been developed and tailored for large dispatchable generation, and does not provide a competitive market for renewable or combined heat and power systems.

To understand grid infrastructure, rate-structure, as well as grid management strategies, it is critical to evaluate how individual alternative energy technologies can be integrated into the overall energy infrastructure to meet individual end uses of electricity, while also possibly meeting other local energy demands (e.g., heating), and contributing to the management of the utility grid (i.e., balancing of the grid load and generation).

The goal of this paper is to evaluate different SOFC-CHP operating strategies from an end-user, grid utility, efficiency and technology perspective. For combined heat and power systems to be effectively deployed, the technology must be considered within the operating interests and business plans of both the utility and the end-user. Neither entity will independently *embrace* the technology if it adds operating cost, unjustified risk, or nuisances during operation, and the technology will not become widely used unless both the utility and end-users benefit. End-users will generally only consider installing distributed generation if the system will provide an operating cost savings. Important parameters in evaluating distributed generation operating cost savings include electricity cost, quality, reliability, and availability as well as savings from heat recovery in combined cooling, heating and power or combined heat and power (CHP) systems. Thus, the sizing and thermal integration of a CHP system is of critical importance to the end-user. From a utility perspective the role of combined heat and power systems in providing reliable and quality electric power for all end-users is of critical importance. If combined heat and power systems

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Nomenclature

C_V	ideal gas constant volume specific heat capacity [kJ kmol^{-1} K^{-1}]
F	Faraday's constant [96,487 C mol^{-1}]
h	enthalpy [kJ kmol^{-1}], convective heat transfer coefficient [kW m^{-2} K^{-1}]
i	current [A]
j	current density [A m^{-2}]
j_0	exchange current density [A m^{-2}]
j_L	limiting current density [A m^{-2}]
k_s	solid conduction heat transfer coefficient
N	control volume molar capacity [kmol]
$\dot{N}$	molar flow rate [kmol s^{-1}]
P	power [kW], pressure [kPa]
$\dot{Q}_{in}$	heat transfer into control volume [kW]
R	universal gas constant [8.3145 kJ kmol^{-1} K^{-1}], control volume reaction rate [kmol s^{-1}], electrical residence [Ω]
T	control volume temperature [K], period [s]
t	time [s]
U_{db}	duct burner usage
U_{fuel}	fuel utilization
V	volume [m^3], voltage [V]
$\dot{W}_{out}$	work out of control volume [kW]
X	species mole fraction

Greek symbols

α	transfer coefficient, price-of-electricity [\$ kWh^{-1}]
β	price of natural gas [\$ m^{-3}]
ϕ	capital cost [\$ kW^{-1}]
φ	annual interest
η	efficiency
τ	payback period [year]

operate base-loaded at the generator max power, other generators or energy resources on the grid must operate increasingly more dynamically to meet the inherent varying grid loads. From a utility perspective the grid impacts of combined heat and power systems must be considered, especially since future grid dynamics will make managing the grid increasingly difficult with increased peak demand and increased penetration of intermittent renewable power [1,2].

The specific system considered is a CHP system based upon use of a solid oxide fuel cell (SOFC). It is well known that CHP systems have the capability to achieve greater than 70% overall system efficiency [3] by generating power near the point of use and recovering the waste heat. High temperature fuel cell systems are particularly attractive for CHP applications [4–6] generating electricity at the small- and large-scale with high fuel to electricity conversion efficiencies, extremely low emissions and also a high quality waste heat that can be recovered and utilized. Two high temperature fuel cell types are common; molten carbonate and solid oxide fuel cells. This paper focuses on solid oxide fuel cell technology.

SOFC systems are electrochemical generators that directly convert the fuel and oxygen chemical potential into electricity. Two other less obvious SOFC attributes that make SOFC-CHP systems particularly attractive are SOFC inherent transient performance capability, and increased efficiency at part load (compared to other fueled generators). If fuel and oxygen is available at the fuel cell triple phase boundary reaction sites, SOFC can respond to load variations at the rate of electrochemical reactions, which is on the order of milliseconds. This theoretically rapid load-following response capability is a major SOFC attribute in providing dynamic and flex-

ible (dispatchable) power from combined heat and power systems. SOFC system efficiency can also increase at part load. This will be shown to play a major role in the economic value proposition associated with part load operation of CHP systems.

2. Background

Deployment of CHP has been globally very low with exception of a few European and east Asian countries. Today, only 8% of total energy in the U.S. is currently produced by CHP plants while more than 50% of electricity is produced by CHP systems in Denmark [7]. The heat generated from electrical power plants in the U.S. is mostly rejected to rivers, lakes and oceans, and an additional energy resource (e.g., natural gas) is used to separately provide heating. The dramatic difference in CHP market penetration between the U.S. and Europe is in part due to climate and in part due to differences in energy policy, electric rate structures, integration and operating rules and regulations of both countries. For example, fossil fuel distributed generators in California must follow distribution generation interconnection Rule 21 [8]. Under this rule, fossil fuel distributed generators cannot dispatch any electricity to the grid. With this restriction, combined heat and power systems are less economically competitive and restricted to a market that has very specific relative electricity and heating demands. To meet interconnection regulations CHP systems must generally be small not taking advantage of economies of scale and often cannot be sufficiently sized to provide back-up power (islanding) capability or sized to produce sufficient heat to meet local thermal demands. Due to this limitation combined heat and power system reliability and efficiency advantages cannot be fully captured making the systems less attractive. However, in Europe combined heat and power systems operate as grid-supporting resources that are typically integrated into district heating loops [9]. Thereby, large units are well thermally integrated and provide flexible electrical energy to the grid providing benefits to both the end-user and the utility [10].

Combined heat and power systems are currently being strongly evaluated for the US. For example combined heat and power is projected to play a big role in California's plan to decrease greenhouse gas emissions under Assembly Bill 32. The electrical infrastructure of the US is already well established, and while district thermal networks as established in Europe may not be feasible, many applications now value a local thermal product. These features, coupled with operating strategies that promote high thermal integration and the potential utility benefits of combined heat and power systems will likely promote higher CHP adoption in the future.

The transformation from large in-basin power plants to distributed combined heat and power plant is particularly attractive for solid oxide fuel cells. While, gas turbine technology efficiency and cost scales up with volume (greatly benefiting larger systems on the order of 500 MW), SOFC technology scales up in power by

Table 1
Different priority requirements of utility, end-user, society and SOFC technology perspectives.

| Perspective	Requirement	How one meets the requirement
Utility	Energy Management	Balance generation and demand including renewables.
End-user	Islanding	Supply electricity without the utility grid.
	Thermal Integration	Supply heat recovering waste heat from generator.
Society	Less Green House Gasses	Achieve high efficiency.
SOFC Technology	Unit Reliability	Enable dynamic load operation.
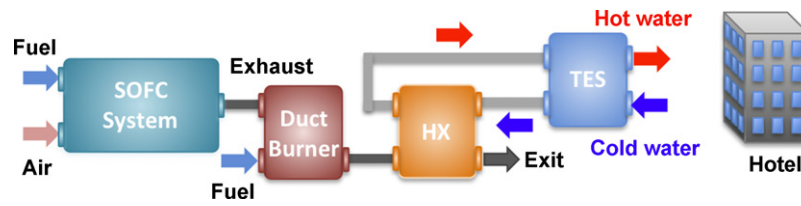
Fig. 1. Schematic of the integrated SOFC-CHP system.

surface area with lower economies of scale. High fuel to electric efficiencies (~60% LHV) can be achieved in 200 kW to 1 MW sized SOFC systems that can be thermally integrated into large buildings, commercial or institutional applications [11]. In addition, these relatively small SOFC systems can produce high quality heat and electricity with very low (virtually zero) criteria pollutant emissions. High efficiency and low emissions at small plant size can provide clean local electric power with high availability and reliability to the end-user and avoid construction of new transmission lines that are increasingly expensive and difficult to site.

In this paper, a dynamic physical model of an SOFC-CHP system is built to evaluate performance (e.g., efficiency, fuel use, dynamic response) for different operating strategies accounting for the physics, chemistry, electrochemistry and interactions amongst system components. Performance of the system is evaluated from an end-user, utility, society, and technology perspective as listed in Table 1. The analysis is conducted using a dynamic physical model of the system as applied to meet measured electrical and heat loads of a hotel in southern California. The model makes it possible to evaluate both the performance of the fully integrated SOFC-CHP system and the benefits of the system from the end-user and utility perspectives. The case studies of the different system designs and operating strategies of the SOFC-CHP system are intended to demonstrate the potential of the technology and provide insights for future technology and policy development.

3. Dynamic model and measured data

A southern California hotel has been selected as a case study to evaluate the operating strategies of SOFC-CHP systems because hotels represent deployment locations for relatively large SOFC-CHP systems that highly value local thermal energy without requiring a new district thermal network. Dynamic building electricity and heating data were measured during the months of July and August in 2008. To investigate the general integration and operation strategy for the SOFC-CHP system, a supplementary exhaust gas duct burner, hot water heat exchanger and hot water thermal energy storage (TES) tank models were developed and integrated into a previously developed 5 kW SOFC model [12].

Each of the component models are developed individually and integrated into the Matlab-Simulink® platform using a fuel

cell system modeling methodology previously developed, verified and used for dynamic system modeling and control development [12–17]. The previously developed simple-cycle SOFC system includes and physically resolves the dynamic governing equations of a steam reformer, blower, heat exchangers, and combustor in addition to the fuel cell stack. Interactions amongst system components are captured to simulate the system dynamic response. The overall system considered in this study is presented in Fig. 1, and important model parameters are summarized in Table 2.

3.1. Measured data

The SOFC-CHP system simulations are conducted on the basis of meeting measured dynamic experimental heat and electricity load data. The heat and electric load demand were measured for the week of July 30, 2008 to August 2, 2008 as shown in Fig. 2. Compared to the electric demand, the magnitude of the heat demand is generally larger (in terms of energy) and varies more dramatically over time. The primary heat demands of the hotel are domestic hot water (i.e., for faucets and showers) and laundry/kitchen heating (e.g., laundry drying). Data were collected every 15 min. The main electric data for the facility is comprised of three separate meter readings. Total electric energy demand is the sum of these 3 meter readings. The boiler load data includes flow rate and supply temperature of the water from the pipeline leading away from the main hotel boilers. A final hot water temperature of 160 °F (344 K) is assumed throughout because this temperature is closely controlled by the hotel boilers (as the measurements indicate).

3.2. Base SOFC model and scale-up

Details regarding the SOFC system model are presented in [12,15–17], hence only a brief summary is provided here. The model is based upon the physics, chemistry and electrochemistry that govern the system, considering conservation of mass, energy. General governing equations used in the model are summarized in Table 2. For the current work, the previously developed 5 kW SOFC system model was scaled up by increasing the number of fuel cells and stacks and the balance of plant component (e.g., heat exchangers, exhaust gas duct burner, and reformer) sizes.

The primary components of the fuel cell system are a reformer, SOFC stacks, a combustor, an air recuperator, and a blower. The

Table 2
General governing equations in the model.

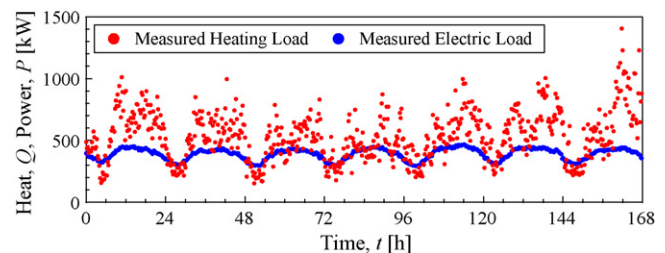|	
Species conservation	$\dot{N}\frac{dX_i}{dt} = \dot{N}_{in}X_{i,\,in} - \dot{N}_{out}X_{i,\,out} + R_i$
Energy conservation	$\dot{N}C_V\frac{dT}{dt} = \dot{N}_{in}h_{in} - \dot{N}_{out}h_{out} + \sum \dot{Q}_{in} - \sum \dot{W}_{out}$
Conducive heat transfer	$\dot{Q}_{cond} = \frac{Aks(T_2-T_1)}{L}$
Convective heat transfer	$\dot{Q}_{conv} = Ah(T_2 - T_1)$
Nernst potential	$E_{nernst} = E^0 + \frac{RT}{nF}\ln\left(\frac{P_{H_2}P_{O_2}^{1/2}}{P_{H_2O}}\right)$
Activation polarization	$V_{act} = \frac{2RT}{nF}\sinh^{-1}\left(\frac{j}{2j_0}\right)$
Ohmic polarization	$V_{ohm} = iR$
Concentration polarization	$V_{conc} = \frac{RT}{nF}\ln\left(\frac{j_L}{j_L-j}\right)$

Fig. 2. The electric and heating load demand, which were obtained from a hotel operated in southern California from 12:00 a.m. on July 27, 2008 to 11:45 p.m. on August 2, 2008.

Table 3
Important Planar SOFC model parameters.

Number of cells	115	–
Width of cell	0.1	m
Length of cell	0.1	m
Depth of bulk gas channels	0.01	m
Thickness of electrolyte	0.005	m
Thickness of gas separator plate	0.005	m
Electrolyte density	5000	$kg\,m^{-3}$
Electrolyte specific heat capacity	0.8	$kJ\,kg^{-1}\,K^{-1}$
Separator plate density	7900	$kg\,m^{-3}$
Separator specific heat capacity	0.640	$kJ\,kg^{-1}\,K^{-1}$
Exchange current density	4,000	$A\,m^{-2}$
Limiting current density	9,000	$A\,m^{-2}$
Transfer coefficient	0.5	–
Resistance	$T\exp[7509.6/T - 25.855]$	Ω

Fig. 3. Exhaust gas duct burner fuel flow rate controller.

fuel cell module is comprised of a hundred of SOFC stacks that are each comprised of 115 planar 10 cm × 10 cm SOFC cells. Each cell operates nominally around 650 mA cm^{-2} and 0.64 V. Simulation of a single unit cell is accomplished and scaled to represent the entire SOFC stack module. Note that the number of stacks varies with the simulation scenarios that will be described the following section. The reformer provides a hydrogen-rich reformate gas to the fuel cell. After the fuel cell stack, the remaining anode off-gas stream is mixed with the cathode depleted air stream, and is completely oxidized in the combustor. The combustor exhaust is directed through the reformer to provide heat to balance the endothermic steam reformation chemical reactions. Within each control volume only the physical and chemical processes that affect the time scales of interest (>10 ms) in the dynamic simulation are considered. Processes such as electrochemical reaction rates and electric current flow dynamics are assumed to occur at a time scale that is faster than that of interest to the model. The fuel cell voltage in the model is determined from the Nernst equation and electrochemical losses: activation, Ohmic, and concentration losses as in [12] using polarization parameters as shown in Table 3. Note that the Nernst equation is solved accounting for local electrolyte temperature and both anode and cathode local species partial pressures.

The generic simple-cycle SOFC system was designed in prior work to evaluate SOFC system control and SOFC inherent transient performance [12,15]. Controls for the system have been previously developed to ensure sufficient reformer temperature, near constant combustor temperature and fuel cell temperature and sufficient fuel within the fuel cell anode compartment during transients and disturbances. The reformer temperature can be well controlled by an appropriate integration of heat exchangers that enable the system to provide sufficient heat to the reformer [12]. Previous studies also show that the combustor temperature can be controlled by manipulating the fuel flow, air flow and fuel cell current. Fuel flow compensation of reformer dynamics is used to manipulate the inlet fuel flow such that sufficient fuel is present in the anode compartment and provided to the combustor for temperature control [12,15]. In fact, it is shown in [15] that the combustor temperature can be maintained to within 20 K for a 1 kW s^{-1}, 50% power increase while maintaining sufficient fuel within the anode compartment. In addition to maintaining the reformer temperature and combustor temperature, the fuel cell positive-electrode electrolyte negative-electrode (PEN) temperature can be maintained to within 1 K for the same perturbation by manipulating the air flow within the fuel cell by varying the blower shaft speed [15].

Models of a supplementary exhaust gas duct burner, hot water heat exchanger, and hot water TES tank have been added to the system model in this work. The duct burner is modeled as a single control volume combustor as presented in [16]. The duct burner is assumed to operate adiabatically with complete fuel oxidation. Note that this duct burner heats up the SOFC exhaust gas, which
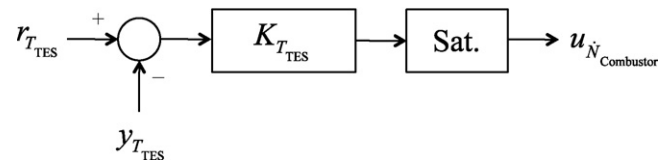
is typically discharged at approximately 490 K. The additional duct burner is only fired when the TES is depleted and the heat generated from SOFC is not sufficient to meet the instantaneous local heating demand. A control methodology for the duct burner is described in the following section. The TES stores hot water above cold water by density difference (thermocline type storage) and is modeled as presented in [18,19]. The molar flow rate and temperature of each control volume of the TES are determined from the appropriate transient energy and mass conservation equations of the same general form. The flow rates throughout the tank are calculated by the mass conservation equation in each control volume. Temperature at each control volume is calculated by solving transient energy conservation equations. Conduction heat transfer between nodes is solved using Fourier's law throughout the model. The properties of water for conduction heat transfer are used. The simulation results in [19] show the dynamic change of the thermoclines in a TES tank compared to the current TES model results, which correspond well to the experimental data in [20]. The hot water heat exchanger has been modeled as a flat plate counter-flow heat exchanger as presented in [16] with no heat loss to the environment. The integrated system model as shown in Fig. 1 resolves the SOFC and balance of plant dynamics representing the transient behavior of a fully integrated SOFC-CHP system.

3.3. Thermal integration

In order to thermally integrate the system with the heat load and control the thermal output of the SOFC-CHP system, a heat recovery system has been modeled and integrated into the SOFC system model. The primary components of the heat recovery physical system model are an exhaust gas duct burner, a hot water heat exchanger, and a hot water thermal energy storage tank. In the overall SOFC-CHP system, heat generated from the SOFC is supplemented by a duct burner to meet the hotel heating demand, using the TES as a thermal storage buffer that independently dispatches hot water to the hotel. Waste heat from the SOFC system is used to heat up the cold water through the hot water heat exchanger. If the heat from the SOFC is not sufficient to meet the hotel heat demand, exhaust gas is heated up before entering the water heat exchanger using additional fuel in the supplementary exhaust gas duct burner. On the contrary, if the waste heat exceeds the heating demand, extra heat is stored as hot water in the TES and then released when demanded. Along with the system component models, controls had to be implemented in the thermal recovery system to meet the heating demand of the application.

As described in [19], two control loops have been added to the original fuel cell model for the system heat recovery components. The first control loop maintains the TES inlet temperature from the heat exchanger at a constant value by controlling the water flow rate of the heat exchanger (Fig. 3). In this work, the hot water set point was 360 K, which is 10 K above the temperature demanded by the hotel. The second control loop maintains the TES outlet temperature above the hotel minimum hot water temperature requirement (350 K) by controlling the duct burner fuel flow rate (see Fig. 4). The duct burner is only fired when the TES outlet temperature is below the demand temperature of the hot water.
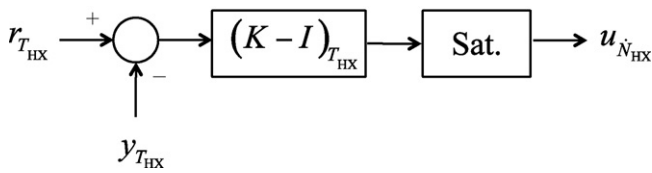
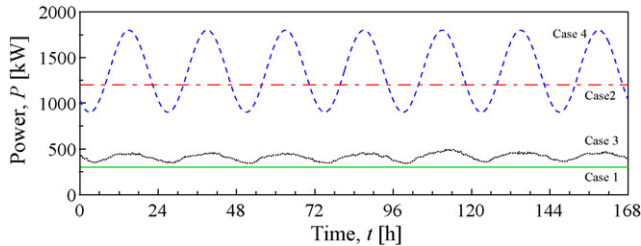**Fig. 4.** Heat exchanger water flow rate controller.

Fig. 5. System integration and operation strategies.

The controller is designed such that when the heat generated from the SOFC is equal to the heating demand, the duct burner is not used. If the SOFC generates more heat than the hotel demands, heat is stored in the TES until the tank becomes full. Once the tank is filled with hot water, the hot water heat exchanger is bypassed and the exhaust gas from the SOFC goes directly into the fuel pre-heater followed by the system exhaust. Meanwhile, if the heat generated from SOFC is not sufficient to meet the heat demand of the load, heat from the TES is dispatched. If the TES becomes depleted and the SOFC heat remains insufficient, the supplementary duct burner is fired to supply the required remaining heat. By physically modeling and controlling the system, the fully thermally integrated system model can effectively simulate SOFC-CHP system performance and efficiency in meeting measured dynamic building electricity and heating demand profiles.

4. System integration and operation strategy

Four operating strategies have been evaluated for the SOFC-CHP system. Key attributes that are evaluated by these operating strategies include: constant or variable power operation, and with or without export of electricity to the utility grid. A summary of the four strategies considered is presented in Fig. 5. In cases 1 and 2, the operating voltage and fuel utilization are maintained at 0.64 V and 0.82, respectively. In cases 3 and 4, both operating voltage and fuel utilization vary depending upon the electric load demand.

Case 1: base-load without power export represents base-load operation of the SOFC-CHP system at a power level that is approximately 10% below the minimum measured electricity demand. This strategy is representative of a CHP operation strategy that complies with Rule 21 requirements [8].

Case 2: base-load with power export represents base-load power operation at a level that produces sufficient heat from the SOFC to meet the maximum measured heating demand with the TES. This value is obtained from a sensitivity analysis that will be discussed in the following section. Since the SOFC power required is greater than the hotel electric demand, power must be exported to the utility grid in this scenario.

Case 3: electric load-following represents the case for electric load-following of the measured hotel electricity demand. As discussed above, recent research on SOFC control shows that an SOFC has the potential to respond to rapid changes in the electric load [15]. This case represents grid independent operation of the SOFC-CHP

system to exactly meet the measured electrical demand of the hotel.

Case 4: grid-support operation represents the case where the SOFC-CHP system is operated dynamically to support grid power management (i.e., export power to the grid when the utility desires such). In addition to dispatching power to the grid, this case represents a system that is sufficiently large to eliminate all supplementary firing of the duct burner. To demonstrate this grid-support concept a sine wave utility grid demand that is in phase with the measured electrical demand (Period, T is the same as that of electric load) as presented Eq. (1) is considered. This type of dispatch profile approximates the case in which the utility desires high power export during times of highest peak demand on the grid. The average power, P_m is determined approximately from the sensitivity analysis that will be shown in the following section. The amplitude of the operating power, P_a is set such that the system power remains between 50 to 100% of maximum rated power previously shown feasible in [21]:

$$P_{SOFC} = P_a \sin\left(\frac{2\pi t}{T}\right) + P_m \qquad (1)$$

5. Scenario results and discussion

The operating strategies described in the previous section have been simulated using the dynamic physical model of the SOFC-CHP system as applied to meet the measured electricity and heating data of the hotel. Through these simulations, the electric and thermal performance of the fully integrated SOFC-CHP system is investigated from utility, end-user, and technical feasibility perspectives.

The amount of heat recovered, $Q_{recovered}$, is defined as the amount of heat from the fuel cell system that is effectively utilized to heat up the hotel hot water supply. Heat from the supplementary duct burner, $Q_{duct\,burner}$ and heat from the SOFC, Q_{SOFC} are calculated by using the following equations, respectively:

$$\dot{Q}_{duct\,burner} = \dot{N}_{add,\,fuel}LHV_{fuel} \qquad (2)$$

$$\dot{Q}_{recovered} = \dot{N}_{Load}C_p\Delta T_{water} \qquad (3)$$

$$\dot{Q}_{SOFC} = \dot{N}_{exhaust}C_p\Delta T_{exhaust} \qquad (4)$$

Note that in Eq. (3), ΔT_{water} is the difference between the temperature of cold water from the pipeline and the temperature of hot water supplied to the heat loop. Meanwhile, $\Delta T_{exhaust}$ in Eq. (4) is the difference between the temperature of the SOFC exhaust gas and the system exit temperature, which is assumed to be 393 K throughout the simulation. Due to this assumption, recovered heat is not necessarily equal to the sum of heat from duct burner and heat from SOFC, with any excess heat leaving through the exhaust.

5.1. Case 1: base-load operation without power export

For Case 1, the total system efficiency achieved by dynamic dispatch of the SOFC heat and constant SOFC power (less than the minimum demand) delivery to meet the measured hotel heat and electricity demands for 1 week is 75.3%. With constant SOFC power operation, the SOFC electrical efficiency remained constant at 45.4%. Fig. 6a shows the dynamic heating demand and supply using heat generated by the SOFC, the supplementary exhaust gas duct burner, and the TES. Although the figure shows the thermally integrated system can meet the heating demand of the hotel, 75% of the heat demand is supplied by the duct burner since the heat from the SOFC system is not sufficient to meet the measured dynamic hot water heating demand. Fig. 6b shows dynamic electricity supply from the SOFC and utility grid. Note that the load requires additional electricity from the grid to meet the demand and that the utility
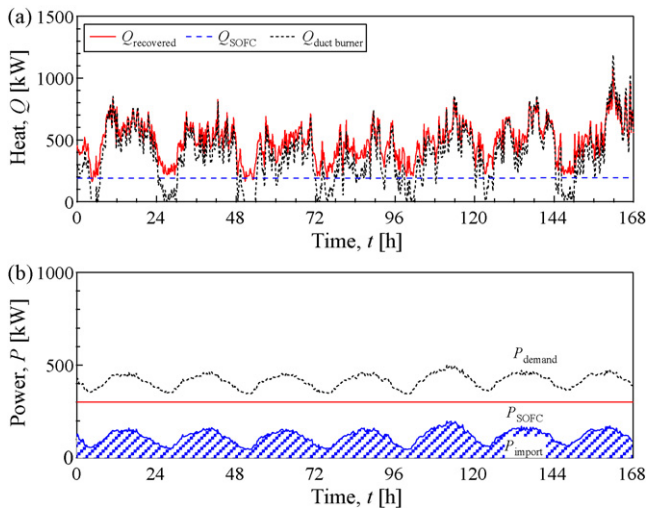
Fig. 6. Dynamic electricity and heating demand and supply for Case 1. (a) Thermal integration. (b) Electrical integration.

must supply less power, but, meet the same dynamic variations in demand (i.e., higher transient/base-load power).

Many jurisdictions throughout the world (e.g., in California) require utilities to accept CHP systems operating in this fashion (i.e., without electricity export to the grid). However, CHP systems operating in this fashion reduce the overall base-load of the grid, introducing a nuisance from utility energy management and utility income perspectives since other generators on the grid would have to operate more dynamically. While the end-user may benefit the operating strategy is not as desirable as it could be. The end-user still has to buy both electricity and additional fuel to burn to meet demands. From an efficiency perspective, this operating strategy is acceptable because it achieves overall higher system efficiency compared to a conventional central power plant plus a boiler. The operating strategy is favorable to the SOFC system since it only requires operation at a constant base-load power.

5.2. Sensitivity analysis

Before moving on to Case 2, the sensitivity of the size of the SOFC unit on CHP system performance is analyzed. Fig. 7 shows the effects of SOFC size on the total system efficiency, η_{sys} (defined in Eq. (5)) and additional duct burner usage, U_{db} (defined in Eq. (6)), which are both calculated as an average value for meeting a week of measured heat and power demand. These values are plotted as functions of SOFC rated output power for various TES capacity values:

$$\eta_{sys} = \frac{\text{Useful Energy}}{\text{Energy In}} = \frac{\dot{W}_{net} + \dot{Q}_{recovered}}{(\dot{N}_{SOFC} + \dot{N}_{duct\,burner})LHV_{fuel}} \quad (5)$$

$$U_{db} = \frac{\int \dot{Q}_{duct\,burner}dt}{\int \dot{Q}_{recovered}dt} \quad (6)$$

The sensitivity analyses suggest that TES size does not significantly affect overall performance, since little difference in η_{sys} is observed for the TES sizes considered. There are slight differences in U_{db} for the TES capacities considered for meeting the given electricity and heating demand trend (Fig. 7). Therefore, in all subsequent cases analyzed herein, the size of the TES tank is fixed to meet the amount of hot water demand for a day, which is approximately 50,000 gallons. The reason that there is little dependence of η_{sys} upon TES size is the following. As shown in Fig. 2, because the heating demand continuously exceeds that which the SOFC can supply during approximately 78% of a day, most of the SOFC heat is used
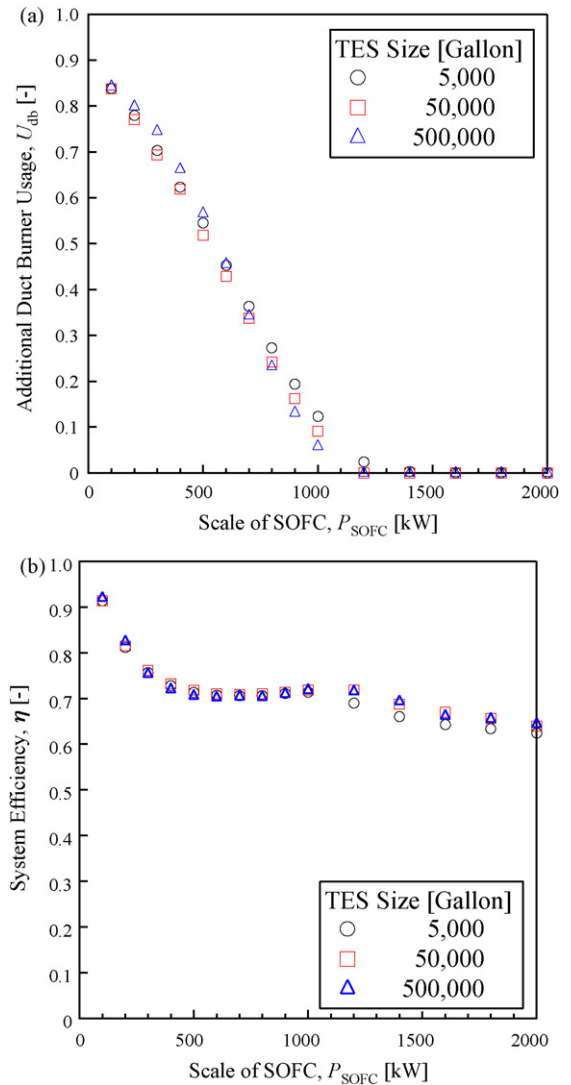

Fig. 7. Sensitivity analysis of SOFC scale (rated size) and TES scale (total capacity) on duct burner usage and system efficiency. (a) Duct burner usage. (b) System efficiency.

directly and only the remaining SOFC heat is stored and shifted to a later use by the TES. In general, the TES tank can only be expected to shift the daily non-coincidence of heat and power if the relative heat and power demands are similar each day (as is the case for the hotel demands considered). If daily heat and power usage were to vary significantly then a larger TES could shift more heat.

Once the tank is sized sufficiently to meet the observed daily non-coincidence, the observed differences in U_{db} are due to mixing in the tank. For a large TES (i.e., a smaller SOFC with a bigger tank), more heat is lost by mixing the hot water with cold water inside the tank. In the model, these phenomena are captured by the mass and energy conservation equations in each control volume. As a result, for most of the simulations in the sensitivity analysis, U_{db} increases with increasing TES scale.

The sensitivity of overall efficiency to SOFC size, P_{SOFC}, is more significant than that to TES capacity. As shown in Fig. 7a, the system does not require additional fuel burning once the SOFC size reaches 1200 kW. This value of 1200 kW is applied for the Case 2 operation strategy as the SOFC rated capacity. Once the SOFC is made larger than this value the overall system efficiency decreases because no additional heat is recovered. The percent change in η_{sys} is smaller than that of P_{SOFC} ($O(\Delta\eta_{sys}/\Delta P_{SOFC}) \sim 10^{-1}$), which implies that the system can achieve relatively high efficiencies even
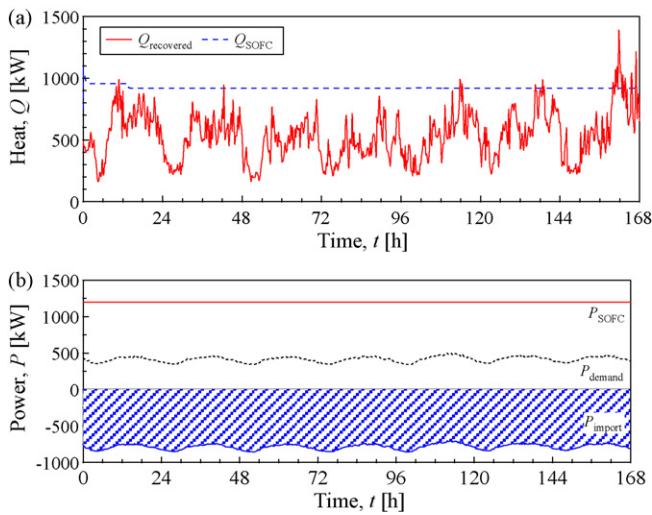
Fig. 8. Dynamic electricity and heating demand and supply for Case 2. (a) Thermal integration. (b) Electrical integration.

though the SOFC is over-scaled (Fig. 7b). Therefore, the slightly higher value of 1350 kW than P_{SOFC} at which U_{db} becomes zero is used in order to demonstrate the grid-support concept in Case 4. The reason for the high overall system efficiency for smaller sized SOFC (i.e., $P_{SOFC} \leq 500$ kW) is that the duct burner is assumed to have an overall efficiency of 95%.

5.3. Case 2: base-load operation with power export

Based on the sensitivity analysis, the SOFC is scaled up to 1200 kW to meet all of the weekly heat demand with SOFC heat. The week-averaged total system efficiency is 71.9%. Fig. 8a shows dynamic heating demand and supply using heat generated by the SOFC. As desired, the use of the supplementary duct burner is no longer required. Fig. 8b shows dynamic electricity supply from the SOFC and utility grid. Negative import power in Fig. 8b indicates export of CHP system power. Although the system has the ability to export electricity to the utility grid at all times, the CHP system does not reduce grid dynamic requirements because of operation at constant high power conditions.

From the utility perspective, this strategy is undesirable because the utility remains completely responsible to manage a more dynamic grid, while at the same time selling less power. In addition, more electricity is exported to the grid when overall grid demand is low, effectively increasing the grid dynamic response requirements. From the end-user perspective, base-load operation with power export is desirable because the end-user can produce both electricity and heat independently from the utility grid and does not need an auxiliary burner. From an efficiency perspective, the operating strategy achieves high system efficiencies without additional fuel burning for heat. From an SOFC technology perspective, it is desirable because of base-loaded operation. Overall, Case 2 is primarily an end-user friendly integration strategy.

5.4. Case 3: electric load-following

The week-averaged SOFC-CHP system efficiency is 78.0% for the electric load-following case. As is shown in Fig. 9a, the system has less duct burner usage compared to Case 1, although it requires use of the supplementary duct burner for the majority of the time to meet the heating demand. The technical capability of an integrated SOFC system to follow the dynamic electricity load is shown in Fig. 9b.
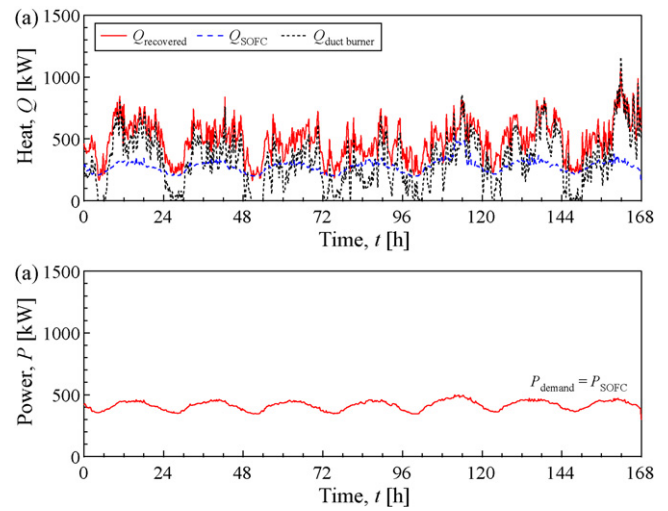

Fig. 9. Dynamic electricity and heating demand and supply for Case 3. (a) Thermal integration. (b) Electrical integration.

From the utility perspective, the electric load-following strategy is acceptable since the hotel appears as a zero load to the grid (except during times of CHP system maintenance or outage). From the end-user perspective, electric load-following is acceptable because the system can independently meet the electricity demand, but cannot produce sufficient heat to meet the heating demand. From an efficiency perspective, electric load-following operation is acceptable but not optimal. Finally, from an SOFC technology perspective, cell degradation/reliability may worsen for dynamic operation, even though the SOFC system can technically follow the dynamic electricity demand. Overall, Case 3 is quite attractive but requires significant SOFC technology advancement to enable electricity load-following.

5.5. Case 4: grid-support operation

The week-averaged SOFC-CHP system efficiency is 87.5% for the grid-support operating strategy, which is the highest value amongst the four scenarios considered. As shown in Fig. 10a, similar to Case 2, the amount of heat from the SOFC alone is sufficient to meet the heating demand.
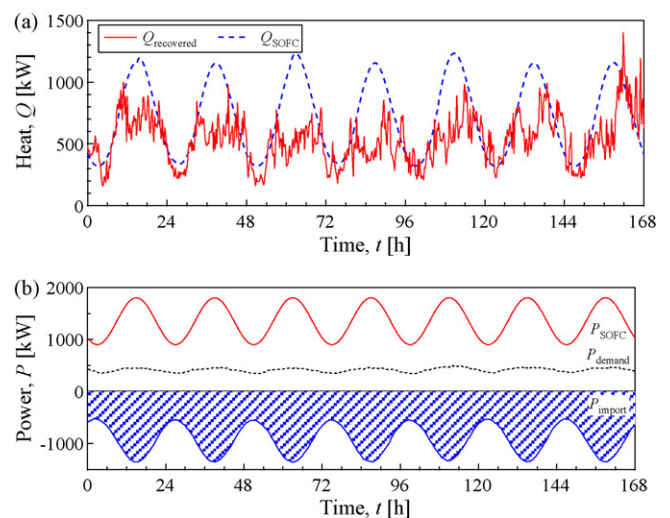

Fig. 10. Dynamic electricity and heating demand and supply for Case 4. (a) Thermal integration. (b) Electrical integration.

Price of natural gas, β	0.3	$ m^{-3}
Gross operating profit, C	0.04, 0.2, 0.4, 2, 4	$ h^{-1}
Lower heating value of methane, LHV_{fuel}	32,820	kJ m^{-3}
Maximum power	4	kW
Operating capacity, x	50–100	%

From the utility perspective, the grid-support strategy is desirable because it can potentially provide local flexible power to help manage the grid (Fig. 10b). However, to enable this type of operation, end-user and utility communication and management rules will have to be established, under which peak export power is appropriately priced so that both parties can benefit. As previously mentioned, an essential point of the grid-support concept is flexible operation. Please note that the SOFC-CHP system capacity chosen in the current case is just one example of the concept. From the end-user perspective, the system provides a reliable source of high quality electricity and heat independently from the utility grid and the potential to receive payments from the utility to dispatch power when it is most desired by the utility. From an efficiency perspective the operating strategy has the highest efficiency amongst the strategies considered, which reduces fuel consumption and greenhouse gases. Lastly from the SOFC-CHP technology perspective, the grid-support strategy may be acceptable as long as the system is operated within a certain range of operating capacity. For example, in terms of the cell temperature distribution associated with variable load operation, the literature shows that the temperature variation can be successfully controlled to a very low level in the range of 40–100% of rated power [21]. In order to optimize the SOFC capacity and operating conditions in the grid-support case, a communication methodology between the utility grid and end-user is required. Overall, the grid-support strategy (Case 4) is desirable to both utility and end-user and produces the best efficiency (and societal benefits of fuel savings and GHG emissions reductions) together with acceptable SOFC technology dynamic operating requirements.

6. Dynamic operation and price-of-electricity (POE)

To demonstrate some of the challenges associated with the cost effectiveness of the grid-support strategy, the effects of dynamic operation of the SOFC (e.g., changing operating capacity of the system) on the price-of-electricity is investigated. In this simple cost analysis, the POE on a $ kWh^{-1} basis is determined to maintain a constant system operating revenue at part load. The system operating revenue is defined as how much the end-user can earn while operating SOFC power plant, and is simply calculated by subtracting fuel cost from electricity dispatch revenue. Therefore, the POE, α in $ kWh^{-1} can be written as

$$\alpha = \frac{C}{xP_{max}} + \frac{3600\beta}{LHV_{fuel}} \frac{1}{\eta_{ele}} \qquad (7)$$

where C is the instantaneous operating revenue in $ h^{-1}, P_{max} is maximum power of the plant in kW, x is the instantaneous operating capacity, β is the instantaneous price of fuel in $ m^{-3}, LHV_{fuel} is the fuel lower heating value in kJ m^{-3}, and η_{ele} is the instantaneous electrical efficiency of the SOFC (Fig. 11a). Constants for the equation and calculation conditions are summarized in Table 4.

A deviation of the POE from the price at maximum power operation $(\alpha - \alpha_{100\%})/\alpha_{100\%}$ is plotted as a function of SOFC operating capacity, x in Fig. 11b. Various fixed operating revenue values are considered. The observed nonlinear behavior is due to changes in SOFC electrical efficiency at part load operating conditions (see Fig. 11a). The results can be explained by the order of magnitude between the first and the second term of Eq. (7). Since the order of
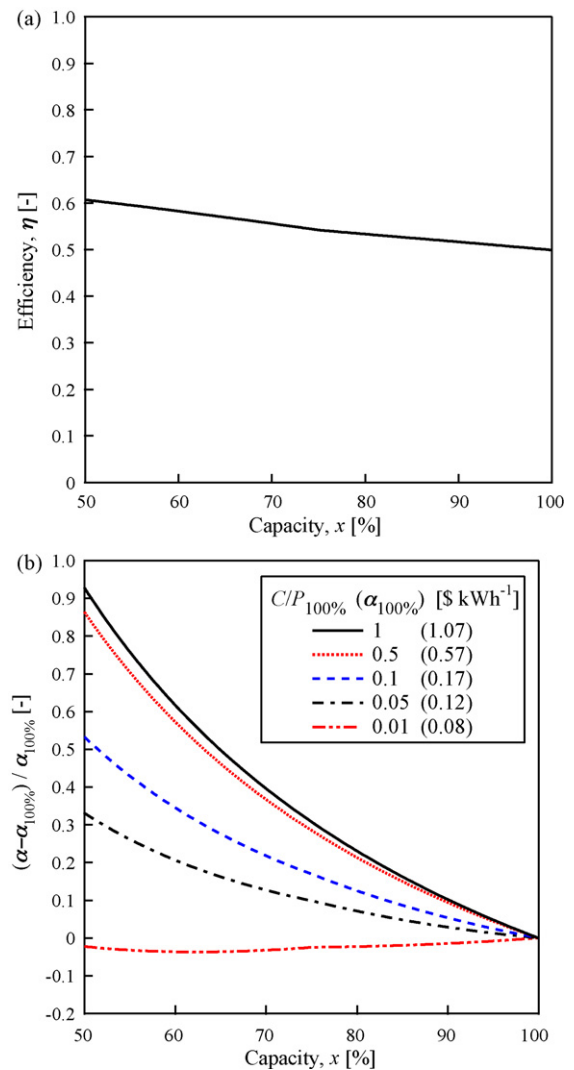

Fig. 11. Effect of dynamic operation of SOFC on simplified price-of-electricity. (a) Electrical efficiency of the modeled SOFC-CHP system. (b) A deviation of the price-of-electricity from that at maximum power operation $(\alpha - \alpha_{100\%})/\alpha_{100\%}$ is plotted as functions of SOFC operating capacity for various gross operating profit values.

magnitude of the second term is approximately 10^{-2}, if the order of magnitude of the first term becomes as small as 10^{-2}, the effect of changes in efficiency are reflected in the POE. If the first term is larger than this order of magnitude, the effect of changes in capacity on POE is much more significant than that of efficiency.

The most recent survey of the California Stationary Fuel Cell Collaborative shows that the current capital cost for fuel cell is approximately 4500 $ kW^{-1} in 2007 [22]. As an example, if the SOFC capital cost (ϕ), payback period (τ), and annual interest (φ) are assumed to be 4500 $ kW^{-1}, 5 years, and 6%, respectively, operating revenue is calculated to be 0.12 $ kWh^{-1}. In this case, as is shown in Fig. 11b, the POE at 50% capacity operation is over 53% higher (26 ¢ kWh^{-1}) than the POE at 100% capacity operation (17 ¢ kWh^{-1}). As another example, if ϕ = 2000 $ kW^{-1}, τ = 5 years, and φ = 6% are assumed, then operating revenue is calculated as 0.05 $ kWh^{-1}. In this case, as is shown in Fig. 11b, the POE at 50% capacity operation is 33% higher (15.4 ¢ kWh^{-1}) than the POE at 100% capacity operation (11.6 ¢ kWh^{-1}). Then, the average POE for load-following according to a sign wave from 50% to 100% capacity (Case 4 operation) is 13.1% higher (13.1 ¢ kWh^{-1}) than the POE at 100% capacity.

Table 5
Summary of four strategies from the different perspectives: utility, end-user, society and SOFC technology.

Perspective	Requirement	Case 1 Base load No export	Case 2 Base load Export	Case 3 Load following No export	Case 4 Various load Export
Utility	Energy Management	Acceptable	Unacceptable	Acceptable	Desirable
End-user	Islanding	Unacceptable	Desirable	Desirable	Desirable
	Thermal Integration	Unacceptable	Desirable	Acceptable	Desirable
Society	Less Greenhouse Gases	Acceptable	Desirable	Desirable	Desirable
SOFC Technology	CHP Unit Reliability	Desirable	Desirable	Unacceptable	Acceptable

Legend: Desirable (green), Acceptable (yellow), Unacceptable (red)

7. Discussion

The developed dynamic model has been used to explore different SOFC-CHP system operating strategies from an end-user, utility, efficiency (producing societal benefits of lower fuel consumption and GHG emissions), and SOFC technology perspective. Table 5 summarizes the different SOFC-CHP system operating strategies from these perspectives. Case 1 represents the current regulatory framework in many regions (e.g., California's Rule 21) and is generally unattractive to the end-user. Case 2 represents a desirable operating strategy for the end-user where a base-loaded fuel cell is sufficiently sized to meet the full thermal load. However, this operating strategy is generally unattractive for utilities. Case 3 resolves this problem by essentially eliminating the need for the utility except during CHP system maintenance or shutdown. This strategy is attractive to the end-user and the utility during operation, but the SOFC technology required to meet the dynamic power demand of this case currently does not exist and supplementary fuel is required to meet the measured heat demands. Case 4 represents grid-support operation of the SOFC-CHP system sized to meet end-user heat demands. The operating concept is shown to be beneficial to both manage utility power demand and meet end-user requirements.

No ideal operating strategy currently exists for SOFC-CHP systems. The integration of the system can greatly benefit from load-following CHP systems. With communication and effective operating agreements with utilities, SOFC system power output can vary slowly to provide needed grid support. This can be particularly attractive since the price-of-electricity increase required by the end-user for constant operating revenue at part load condition is nonlinear with load. Due to the increase in efficiency at part load, the price-of-electricity required only increases 33% for a 50% reduction in power. In this grid-support operating strategy, the SOFC system is sized to meet end-user specifications and operated to provide grid support. The added value of increasing the SOFC size to enable grid support can be very attractive to the end-user and the utility. Flexible SOFC operating power is essential to benefit both the end-user and the utility. In this way, SOFC systems can provide high efficiency, affordable and flexible power with ultra-low emissions that no other technology may be able to generate.

Future work to enable this grid-support operating strategy of SOFC-CHP system includes: (1) development of SOFC technology that can change power over time including the impact of SOFC transient operation on SOFC system probability of failure and degradation, (2) a communication strategy between end-users and the utility to both vary system power to support the grid, and ensure appropriate thermal integration of the system, (3) strategies to integrate and maintain distribution grid infrastructure reliability and power quality with distributed generation, and (4) policy advancements that promote the use of combined heat and power from an end-user and utility perspective (e.g., allow dispatch, provide time of dispatch pricing).

8. Conclusions

In order to understand system operating limits and improve flexibility, a dynamic model of an SOFC-CHP system has been developed. The model has been used to evaluate SOFC-CHP system operating strategies from a utility, end-user, efficiency and SOFC technology perspective. The simulation results indicate the following findings:

(1) An SOFC-CHP dynamic system model has been shown to be a useful tool to understand the limits and flexibility of the system as well as create and explore integration and operation strategies. While measured electricity and heating data of a hotel is used as an application example in this study, the model has the potential to be immediately applied to other applications.
(2) The grid-support strategy is shown to be able to achieve greater than 80% overall system efficiency with export of electricity to the utility grid. This strategy increases the operational flexibility of the SOFC-CHP system to support the grid especially as increasingly intermittent renewable power is added.
(3) If the SOFC-CHP system is operated in the range of 50–100% capacity in the current application, the average change in the price-of-electricity required to support end-user cost effectiveness of grid dispatch is only about 13.1% of the price-of-electricity at the maximum power operation.

In order to implement grid-support operation, a smart communication and control methodology between the utility grid and the end-user is required. Once this link is established, other ancillary services, such as voltage regulation, could be provided from the utility perspective. The impacts of these operating strategies upon SOFC-CHP system reliability must be evaluated. However, the technology and operating strategy are shown herein to potentially supply high efficiency, affordable, local and flexible electric generation with ultra-low pollutant and GHG emissions. Grid infrastructure, rate-structure, and policy developed around large central power fossil fuel generation should be re-evaluated to support advances in energy technology, such as those investigated herein.

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