Energy and Buildings 61 (2013) 153–160

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Potential of SOFC CHP systems for energy-efficient commercial buildings

E.J. Naimaster IV, A.K. Sleiti*

University of North Carolina at Charlotte, Department of Mechanical Engineering and Engineering Science, 9201 University City Boulevard, Charlotte, NC 28223, United States

ARTICLE INFO

Article history:
Received 5 November 2011
Received in revised form 12 July 2012
Accepted 6 September 2012

Keywords:
Solid oxide fuel cells (SOFCs)
Cogeneration
Energy efficiency
Commercial buildings
Combined heat and power

ABSTRACT

An energy-efficient and low-emissions solid oxide fuel cell (SOFC) combined heat and power (CHP) system is a promising electric and thermal energy generation technology for implementation in future commercial buildings.

Recently developed performance models for kW- and MW-sized SOFC CHP systems have been integrated into a building energy simulation model of a medium-sized (7000 m^2) office building to evaluate the potential of the system to lower annual utility costs and to reduce CO_2 emissions. An optimized 175 kW SOFC CHP system successfully lowered annual utility costs by up to 14.5% over a baseline HVAC system in locations with space heating-dominant loads. Potential CO_2 emissions were reduced by up to 62% over the baseline case for the optimized SOFC CHP systems.

If the capital and installation costs of SOFC CHP systems are reduced in the near future, through the realization of cheaper, high-performance intermediate temperature SOFCs, the SOFC CHP system may be a promising energy-efficient and low-emitting alternative power and thermal energy cogeneration technology.

1. Introduction

With rising energy costs and increasing awareness of harmful emissions from traditional energy production, there is a growing movement to increase the energy efficiency and decrease the overall energy consumption of buildings in the US. The US Department of Energy's Building Technologies Program has set forth an ambitious goal of realizing market-viable net-zero energy commercial buildings by 2025 [1]. Also, the US, as part of the Copenhagen Accord, has committed to reducing energy-related CO_2 emissions 17% from 2005 levels by 2020 [2]. This is part of a long-term plan that sees US-based CO_2 reductions on the order of 80% by 2050.

1.1. Commercial building energy consumption in the US

There are more than 5.5 million commercial buildings in the US, and they account for 19% of all energy consumption and energy-related CO_2 emissions [3]. The demand for electricity from buildings in the US was the driving force behind a 58% growth in net domestic electricity generation between 1985 and 2006 [4]. Even relatively small increases in the energy efficiency of new commercial buildings would translate into meaningful energy savings and CO_2 emissions reduction for the US as a whole.

Among the different types of commercial buildings, office buildings in particular consume the most energy and, therefore, produce the most CO_2 emissions [5]. The energy consumption by end-use for an average commercial building shows that heating, ventilating, and air-conditioning (HVAC) systems are the largest consumer, around 32% of the building total [4]. Studies found in literature where commercial building-sized HVAC systems are investigated for their energy efficiency, overall energy consumption, and CO_2 emissions reduction capabilities show promising results for solid oxide fuel cell (SOFC)-based cogeneration, or combined heat and power (CHP), systems.

1.2. SOFC and HTFC CHP systems in commercial buildings

SOFCs are solid-state fuel cells with no moving parts and, unlike fossil-fueled technologies, are not limited by a Carnot efficiency, which means combined electric and thermal efficiencies of greater than 90% can be reached [6]. SOFC stacks are well-suited for applications in distributed generation (DG), or localized stationary, power applications, as the high operating temperature (600–1000 °C) allows for operation on conventional hydrocarbon fuels (e.g. natural gas) with internal reforming and the production of high-quality exhaust waste heat for cogeneration. [6]. If operating with natural gas as fuel, SOFCs can eliminate almost all NO*x*, SO*x*, and particulate matter emissions, and reduce CO_2 emissions by up to 54% in comparison to traditional fossil-fueled power plants [6]. These

* Corresponding author at: 9201 University City Boulevard, Smith 271, Charlotte, NC 28223, United States. Tel.: +704 687 2931.
E-mail addresses: enaimast@uncc.edu (E.J. Naimaster IV), asleiti@uncc.edu (A.K. Sleiti).

0378-7788/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.enbuild.2012.09.045

properties of SOFCs make them valuable for power generation scenarios where high power reliability is needed, emission minimization or elimination is required, or biological waste gases are available for fuel [6].

SOFC stacks have successfully been tested in long-term stationary power applications up to the MW-scale, typically for use in commercial CHP applications [6,7]. SOFC CHP systems allow the waste exhaust gas thermal energy from the SOFC stack to be used for heating a building's hot water loop or even for operating a gas turbine, thereby increasing the overall efficiency of the system [8]. Numerous recent studies on SOFC CHP system modeling and simulation indicate the growing interest in determining their potential for high-efficiency buildings.

Numerous recent studies on SOFC CHP system modeling and simulation indicate the growing interest in determining their potential for high-efficiency buildings.

In 1998, Riensche et al. [9] performed an energy and economic analysis for a natural gasfueled 200 kW SOFC and balance-of-plant (BoP) model, which includes the components for air and fuel supply, power conversion, exhaust gas removal, fuel processing units, heat exchangers, and control systems [9]. The SOFC stack operated at a temperature of 850 °C with a fuel utilization of 80%, assuming 50% internal reforming [9]. Static efficiency values of 43% and 67% were calculated for the electrical efficiency and total efficiency of the SOFC CHP system, respectively, from the model as no part-load performance for the SOFC stack was considered [9]. Riensche et al. investigated the effects of different SOFC operating parameters, including fuel reforming type, operating temperature, and fuel utilization, on the system efficiency and cost of electricity produced by the SOFC using their model. They were able to able to reduce the cost of electricity for the system most significantly when internal reforming and ideal fuel utilization conditions were considered, on the order of 50% and 20%, respectively [9].

In 2004, Fontell et al. [8] performed a conceptual study of a natural gas-fueled 250 kW SOFC CHP system. They considered a SOFC stack and BoP model using a proprietary heat and mass balance program. Similar to the previous study by Riensche et al., only the SOFC stack and BoP components are considered, i.e. there were no loads attached to the system. The SOFC stack was modeled as a "black box" and the actual physics of the SOFC operation were not considered. The SOFC electrical efficiency was determined to be 47% with a total system efficiency of 80–85% [8]. No part-load operating conditions were considered. The target system cost (for 2010) was an aggressive $500/kW [8].

From the analysis of their SOFC CHP model, Fontell et al. found that, for commercial markets, the investment cost of an industrial SOFC power unit must be below €1500/kW, assuming SOFC efficiencies of 55% and 90% for electrical and co-generation are achieved [8]. This value was determined based on a SOFC lifespan of 25 years, 7% interest rate, and a natural gas price of €17/MWh [8]. It was also found from their BoP study that the performance and cost of the cathode heat exchanger and power electronics are critical to the SOFC CHP system efficiency and cost [8].

Although there are many studies involving SOFC-based CHP systems, there are few that integrate fuel cell CHP system models or data with a building energy simulation programs [10]. This type of simulation allows for the integration of a SOFC CHP model into a realistic building energy model with accurate building loads and profiles, as well as the consideration of local climate and utility rates. This is a critical step in determining the potential functionality and economic viability of a fuel cell CHP system for use in commercial buildings.

Braun et al. [11] evaluated different SOFC micro-CHP systems for residential applications in 2006. They considered five different system designs for optimal thermal-to electric ratios (TERs) with residential domestic hot water (DHW) systems, including different fuel types and different fuel reforming strategies. No building loads were considered in the analysis process; instead, the performance of the SOFC CHP systems was optimized by their TER, where a TER of 0.7 – 1.0 was considered optimal for matching residential DHW loads [11].

Braun et al.'s SOFC stack model was a scaled-up version of a validated steady-state, 1-D, single cell energy balance. The single cell SOFC model considered an anode-supported design with an yttria-stabilized zirconia (YSZ) electrolyte [11]. In operation, the SOFC temperature was modeled at 800 °C, with a fuel utilization of 85% [11]. Part-load performance of the SOFC stack was not discussed. The heat loss from the SOFC stack was assumed to be 3% of the fuel input [11].

In their analysis, Braun et al. found that internal reforming of the methane fuel reduced the needed cathode air mass flow rate by 50% and also produced the highest electrical efficiency, although a slight decrease in overall efficiency was seen [11]. The results can be validated by the Riensche et al. [9] study, as the highest electrical efficiency in their study did not necessarily correspond to the lowest cost of electricity.

Also in 2006, Alanne et al. [12] investigated the financial viability of a natural gas-fueled 5 kW micro-CHP system from Fuel Cell Technologies, Ltd. for a simulated 240 m^2 house located in Ottawa and Vancouver, Canada. The buildings were simulated with HOT2000, a building energy simulation program; however, since there is no tool in the program to simulate a SOFC CHP system, a model was developed externally in Microsoft Excel based on the HOT2000 output results [12]. The group focused on the determining the maximum allowable capital cost to be competitive with electric and gas prices for the studied locations [12].

The SOFC CHP model was based on an energy balance for the SOFC stack and associated components, which included the SOFC stack, an air handling unit, a fuel processing unit, and a seasonal thermal energy storage tank [12]. The electrical efficiency and power of the SOFC CHP system was determined by a simple parametric relation instead of through an actual model of the SOFC electrochemical processes [12]. The SOFC stack power was varied from 1 to 5 kW, where the stack was run constantly at full capacity, instead of following the thermal or electrical loads, for simplicity [12]. It was assumed that 6% of the output power was required for ancillary equipment [12]. Assuming a maintenance cost of $(CAD)0.01/kWh, payback periods of 5–20 years, and 3–10% interest rates, only 1–2 kW SOFC CHP systems were economically justifiable in Ottawa [12]. Due to the lower electric and natural gas prices in Vancouver, none of the SOFC CHP systems were economically feasible [12]. This study highlights the importance of utility rate structures to the energy savings potential of SOFC CHP systems.

In 2007, Hawkes et al. [13] investigated economically optimal operating strategies for a natural-gas fueled 5 kW SOFC micro-CHP system for residential space and water heating in the UK. The alternative operating strategies were developed since it was noticed that the cyclical residential heat patterns during the morning and night in the UK were not conducive to SOFC performance, which is best suited for constant loading [13]. They considered an intermediate temperature, direct internal reforming SOFC stack and the BoP model.

gPROMS ModelBuilder was used to develop SOFC stack part-load efficiency curves from the group's previous research developing a steady-state, 1-D single cell SOFC model based on a mass and energy balance [13]. The group considered part-load electrical, thermal, and cogeneration efficiency curves in their SOFC micro-CHP system model.

Their model focused on a 5 kW SOFC stack with a fuel utilization of 70%, electrical parasitic and heat losses of both 200 W [13]. The residential heat demand was simulated using Tas, a BESP from Environmental Design Solutions, Ltd. [13]. Different heat demand