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Selection of prime mover for combined cooling, heating, and power systems based on energy savings, life cycle analysis and environmental consideration

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ABSTRACT

Selection of prime mover type was investigated for use in combined cooling, heat and power systems. Selection was determined from comparison of performance criteria for economic, energy and emissions savings. Simulations were run for three different types of prime movers in one climate zone and compared to a reference case with a typical separate heating and power system in the same climate zone. A hybrid load following method was implemented, with a suggested improvement. Performance parameters were compared and results indicated emissions and energy savings for all three prime movers. The prime mover types were reciprocating internal combustion engine (ICE), micro-turbine and phosphoric acid fuel cell. The climate zone was chosen to be a cold, humid climate represented by Chicago, IL. Economic savings were seen for both the ICE and micro-turbines. Emissions savings for carbon, nitrogen-oxides and methane, for all three types, were greater than 9%, 12%, and 13%, respectively. Primary energy consumption savings for all three were greater than 8%.

1. Introduction

Cogeneration or combined heat and power (CHP) systems are implemented throughout the United States. They allow for the utilization of waste heat from the on-site generation of electricity. The waste heat is used to help meet the thermal demands of the building. Similarly with the use of absorption chillers, the waste heat can also be used to help meet the cooling demands of a building. This is known as combined cooling, heating and power (CCHP) or trigeneration. The Department of Energy is currently working toward a goal of increasing CHP capacity by 40 GW by the year 2020 [1].

Combined systems must run on some sort of load following scheme. For systems with a single prime mover schemes that follow the electric load or that follow the thermal load is often used [2,3]. Smith and Mago [4] evaluated the performance of a hybrid scheme that followed either the electric load or the thermal load in a given time period. The results show that efficiency is improved by using the hybrid load following scheme, leading to efficiencies around 80%. It is also possible to use base loading [5] where the prime mover is run at a constant base loading, or to use multiple prime movers with one operating at a base load with the other operates under one of the load following schemes [6].

Such sytems are largely found in industrial settings [7], but can also be implemented in a variety other building types and sizes. Studies from Mago and Luck [8] and Kavvadias et al. [9] both evaluated the benefits of combined systems in hospital buildings. Knizley et al. [10] used a restraint building to illustrate the benefits of using dual prime movers in a combined system. Smith and Mago [4] demonstrate the use of different load following strategies for a large hotel. Mago et al. [11] evaluated the use of micro-CCHP (<30 kW) and determined that the use of hybrid load following had the best-simulated performance. Because of physical limitations, according to Ebrahimi and Keshavarz [12], hybrid load following on such a small prime mover may not be feasible, and they propose a sizing and load following strategy to make the use of CCHP in a multi-unit residential building feasible. Many of these studies focus on the optimization of combined systems regarding size of prime mover and load following strategies [13–15]. The current study seeks to present a strategy for selecting the type of prime mover to be used, e.g. combustion engines, turbines, etc.

The operation of a CCHP system, and thus the choice of prime mover, depends on several parameters. These include the climate zone, building thermal and power demands, costs of fuel compared to electricity, the availability to sell excess electricity back to the

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Nomenclature

AC	Absorption chiller
AOC	Annual operating cost
AS	Annual savings
CC	Compression chiller
CCHP	Combined cooling, heating, and power
CDE	Carbon dioxide emissions
COP	Coefficient of performance
Em	Emission
EUAC	Equivalent uniform annual saving
F	Fuel
HE	Heat exchanger
HC	Heating coil
IC	Initial cost
ICE	Internal Combustion Engine
IRR	Internal rate of return
MARR	Minimum attractive rate of return
ME	Methane emission
NXE	Nitrogen oxide (NO_x) emission
PM	Prime mover
SEC	Site energy consumption
SPP	Simple payback period
SS	Spark spread
COP_{AC}	Coefficient of performance of absorption chiller
COP_{CC}	Coefficient of performance of compression chiller
$C_{NG,elec}$	Cost of natural gas/electric per kWh
C_{om}	Cost of operation and maintenance except fuel per kWh
E_B	Total electricity supplied from grid and the prime mover
E_{CC}	Electricity supplied to compression chiller
E_{ED}	Building electricity demand except the chiller electricity requirement
E_{Grid}	Electricity purchased from grid
E_{PM}	Electricity generated by the prime mover
$E_{PM\max}$	Rated capacity of the prime mover
E_R	Electricity supplied to the building except compression chiller
Em_s	Emission savings
F_{boiler}	Fuel consumed by the boiler
F_m	Fuel required for both the boiler and the prime mover
F_{PM}	Fuel consumed by the prime mover
L_{PM}	Lifetime of the prime mover
P_{PM}	Prime mover rated capacity
Q_{AC}	Cooling energy supplied to the building by absorption chiller
Q_{Boiler}	Heating energy supplied by the boiler
Q_{bld_D}	Design thermal demand for the building
Q_{CC}	Cooling energy supplied to the building by compression chiller
Q_{CD}	Cooling load demand
Q_{HD}	Heating load demand
Q_{HE}	Heat recovered from the heat exchanger
$Q_{HE\max}$	Maximum possible heat extraction from the heat exchanger
Q_{HEopt}	Optimum heat extraction from the heat exchanger to meet the prime mover electric load
Q_{PM}	Waste heat energy available from prime mover
η_{HE}	Heat exchanger efficiency
η_{Boiler}	Boiler efficiency
η_{HC}	Heating coil efficiency
ψ	Factor of heat losses from prime mover to heat exchanger
ξ	Interest rate

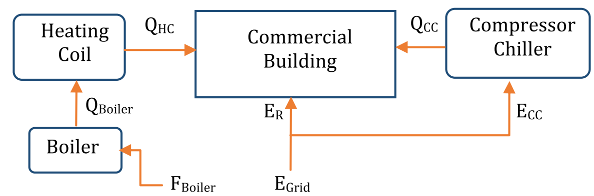

Fig. 1. Schematic of reference system.

grid excess electricity, and the capability for electric or thermal storage [4,5,11,12,16–22]. Sanaye et al. [20] studied the selection between diesel engine, gas engine and gas turbine prime movers with electric load following, with and without the ability to sell back electricity, but did not evaluate the use of fuel cell prime movers. Yang et al. [23] investigated how the use of fuel cell generators, used in combination with ground source heat pumps, could produce primary energy consumption savings, while potentially also yielding operational savings. An in-depth analysis of HVAC systems is not included in this study, as several studies have addressed this [24–27].

The current study investigates the use of CCHP in a cold, humid climate (Chicago, IL) for a medium sized office building with an operational strategy and does not consider power storage or the ability to sell back electricity. This study seeks to outline the process and parameters for choosing which type of prime mover (reciprocating engines, gas turbines or fuel cell prime movers) to use for a single prime mover setup run with a hybrid load following scheme. Additionally an improvement on the hybrid load following method is presented, where the non-constant relationship between efficiency and partial loading of the prime mover is considered. Electricity sellback was not considered in this study because the hybrid load following method used does not result in excess electricity generation. Thermal storage was not included in this study because it is expected that the use of thermal storage would generally improve the cost, energy consumption and emissions for all types of prime movers [5].

Results from simulations for different prime movers are compared to a reference separate cooling, heating and power system. They are evaluated in terms of economic, energy conservation and emissions mitigation. Parameters indicating cost savings are the simple payback period (SPP), annual savings (AS), internal rate of return (IRR) and equivalent uniform annual savings (EUAS). The energy savings parameter used is primary energy consumption (PEC). As indicated by the results from Fumo et al. [28], site energy consumption (SEC) will always increase when CCHP is used, while PEC can still be decreased, and thus PEC is a better indicator of system feasibility. Finally, emissions savings are determined for carbon dioxide ($Em_{s,CD}$), nitrogen oxides ($Em_{s,NX}$), and methane ($Em_{s,M}$).

2. Methodology

2.1. CCHP system model

A typical separate cooling, heating and energy system is illustrated in Fig. 1 for comparison with the proposed CCHP system. A schematic of the proposed system is illustrated in Fig. 2. The associated equations for the system are developed as follows.