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# Optimal operation of a residential district-level combined photovoltaic/natural gas power and cooling system

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## HIGHLIGHTS

- Study feasibility of a CHP plant with PV integration in a hot climate.
- Demand data collected from large-scale smart grid demonstration site.
- CHP plant model based on existing operating facility.
- CHP with district cooling can meet residential neighborhood energy demand in the Southwest United States.

## ARTICLE INFO

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## ABSTRACT

Combined heat and power (CHP) facilities are a very promising path to reducing $CO_2$ emissions and increasing efficiency in the power generation sector. The ability to supply essential residential utilities (electricity, cooling, and heating) in an efficient manner opens the way for combining district cooling, heating and power generation, and suggests that CHP plants are an attractive choice for providing integrated utilities for the neighborhood of the future. In this paper, we describe the optimal integration of a CHP plant as a utility producer for a residential district, and the potential for combining CHP with photovoltaic power generation. Utilizing residential energy demand data collected by Pecan Street Research Inc., a smart-grid demonstration project in Austin, TX, residential heating, cooling, and electricity demand are analyzed and evaluated. These demands are then used to compute an optimal operating strategy for an integrated CHP/solar utility and the impact of photovoltaic generation on plant operation and operating profit is determined. We demonstrate that CHP is a viable means for providing district-level cooling, heating, and power to a residential district in a hot climate.

## 1. Introduction

Of the energy consumed in the United States, 20.10 quadrillion BTU (21% of the total energy consumption) are delivered for residential use. According to the data provided by the U.S. Energy Information Administration, a staggering 9.68 quadrillion BTU are lost [1]. Approximately 48% of these losses are due to electricity related inefficiencies. This number, calculated using data from all across the United States, can vary from region to region. Shown in Fig. 1, Austin, TX can experience energy losses of over 67% from coal power plants, and additional losses can be incurred during power transmission and its conversion to heating, cooling, and ventilation for residential homes.

Government agencies, industry, and academic researchers been working to increase efficiency at the household level (e.g. energy-efficient appliances, retrofitting older homes) and shift energy demand from peak times to periods of lower demand. One possible solution to improve efficiency is to use Combined Heat and Power (CHP) with district cooling for residential neighborhoods. CHP plants are over twice as efficient than coal-fired power plants, reaching efficiencies of 80% [5]. The CHP plant can be located near the neighborhood, minimizing transmission losses. Finally, with district heating and cooling produced from the plant, efficiency losses caused by oversizing or undersizing of residential HVAC units are eliminated.

In the industrial sector, CHP is commonly used with processes that have large concurrent heat and power demands, such as chemical [6,7], pulp and paper [8], food [9], textile [10], and minerals [11] [12]. In the commercial buildings sector, CHP plants can be found in areas with many businesses and lodging in close

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## Nomenclature

*Sets*

| | |
|---|---|
| $H$ (index $h$) | The set of hours used in the scheduling |
| $C$ (index $c$) | The set of components scheduled, $\{GT, BR, EC, SA\}$ |
| $M$ (index $m$) | The set of modes, $\{on, off, cold\ startup, warm\ startup\}$ |

*Variables*

*Binary variables*

| | |
|---|---|
| $y^h_{c,m}$ | Component $c$ is in mode $m$ at hour $h$ |
| $V^h_{c,cold}$ | Cold startup has begun at hour $h-1$ for component $c$, and continues at hour $h$ |
| $V^h_{c,warm}$ | Warm startup has occurred at hour $h-1$ for component $c$ |

*Continuous variables*

| | |
|---|---|
| $IGV^h$ | Inlet guide vane angle of the inlet air cooler at hour $h$ (rad) |
| $Vw^h$ | Volume of water entering the inlet air cooler at hour $h$ (GPM) |
| $m^h_{air}$ | Mass of the air exiting the inlet air cooler at hour $h$ (kg/s) |
| $T^h_{air,out}$ | Temperature of the air exiting the inlet air cooler at hour $h$ (°C) |
| $Fd^h$ | Fuel signal of the gas turbine at hour $h$ (fraction of nominal flow) |
| $P^h_{GT}$ | Power generated by the gas turbine at hour $h$ (kWh) |
| $T^h_f$ | Firing temperature of the gas turbine at hour $h$ (°C) |
| $T^h_e$ | Temperature of the exhaust gas exiting the gas turbine at hour $h$ (°C) |
| $W^h_{f,HRSG}$ | Fuel flow into the HRSG at hour $h$ (kg/s) |
| $W^h_{sh,HRSG}$ | Mass flow of steam exiting the HRSG at hour $h$ (thousand lb/hr) |
| $T^h_{sh,HRSG}$ | Temperature of steam exiting the HRSG at hour $h$ (°C) |
| $T^h_{e,HRSG}$ | Temperature of exhaust gas exiting the HRSG at hour $h$ (°C) |
| $W^h_{f,BR}$ | Fuel flow into the boiler at hour $h$ (kg/s) |
| $W^h_{sh,BR}$ | Mass flow of steam exiting the boiler at hour $h$ (thousand lb/hr) |
| $W^h_{sh,SA}$ | Mass flow of steam entering the steam absorption chiller at hour $h$ (thousand lb/hr) |
| $Q^h_{SA}$ | Cooling produced by the steam absorption chiller at hour $h$ (Btu) |
| $P^h_{EC}$ | Power supplied to the electric chiller at hour $h$ (kWh) |
| $Q^h_{EC}$ | Cooling produced by the electric chiller at hour $h$ (Btu) |
| $PowerRev.Ext.^h$ | Revenue from selling electricity to the grid at hour $h$ (\$) |
| $PowerRev.Int.^h$ | Revenue from selling electricity to the neighborhood at hour $h$ (\$) |
| $CoolingRev.^h$ | Revenue from selling cooling to the neighborhood at hour $h$ (\$) |
| $HeatingRev.^h$ | Revenue from selling heating to the neighborhood at hour $h$ (\$) |
| $P^h_{ext}$ | Electricity sold to the grid at hour $h$ (kWh) |
| $FuelCost^h$ | Cost to purchase fuel at hour $h$ (\$) |
| $CostTimeLost^h_c$ | Cost of transitioning from off to on for component $c$ at hour $h$ (\$) |

*Parameters*

| | |
|---|---|
| $T^h_{w,in}$ | Temperature of the water entering the inlet air cooler at hour $h$ (°C) |
| $T^h_{air,in}$ | Temperature of the air entering the inlet air cooler at hour $h$ (°C) |
| $IGV^{max}$ | Maximum angle of the inlet guide vane (rad) |
| $IGV^{min}$ | Minimum angle of the inlet guide vane (rad) |
| $Vw^{max}$ | Maximum volume of water to enter the inlet air cooler (GPM) |
| $Fd^{max}$ | Maximum fuel signal (fraction of nominal flow) |
| $Fd^{min}$ | Minimum fuel signal (fraction of nominal flow) |
| $P^{max}_{GT}$ | Maximum power from the gas turbine (MW) |
| $kNL$ | Fuel valve lower limit for the gas turbine (fraction of nominal flow) |
| $W_{f,0}$ | Fuel flow at nominal operating condition (kg/s) |
| $W^{max}_{f,HRSG}$ | Maximum fuel flow entering the HRSG (kg/s) |
| $W^{max}_{f,BR}$ | Maximum fuel flow entering the boiler (kg/s) |
| $W^{min}_{f,BR}$ | Minimum fuel flow entering the boiler (kg/s) |
| $P^{max}_{EC}$ | Maximum power supplied to the electric chiller (kWh) |
| $P^{min}_{EC}$ | Minimum power supplied to the electric chiler (kWh) |
| $W^{max}_{sh,SA}$ | Maximum steam supplied to the steam absorption chiller (thousand lb/hr) |
| $COP_{SA}$ | Coefficient of performance for the steam absorption chiller |
| $H_{out,HRSG}$ | Enthalpy of steam exiting the HRSG (kJ/kg) |
| $H_{out,SA}$ | Enthalpy of steam exiting the steam absorption chiller (kJ/kg) |
| $\hat{H}_{sh,BR}$ | Enthalpy of the steam exiting the boiler (kJ/kg) |
| $\hat{H}_{i,BR}$ | Enthalpy of the water entering the boiler (kJ/kg) |
| $P^h_{int}$ | Electricity needed by the neighborhood at hour $h$ (kWh) |
| $Q^h_{int}$ | Cooling needed by the neighborhood at hour $h$ (Btu) |
| $W^h_{sh,HT}$ | Steam needed by the neighborhood for heating at hour $h$ (thousand lb/hr) |
| $P^h_{solar}$ | PV generation from the neighborhood at hour $h$ (kWh) |
| $Trans\ Cost_c$ | $m' \times m$ matrix with the costs to transition from mode $m'$ to mode $m$ for component $c$ |
| $WarmCost_c$ | Cost to turn on a component through a warm startup for component $c$ (\$) |
| $ColdCost_c$ | Cost to turn on a component through a cold startup for component $c$ (\$) |

proximity, such as hotels [13], hospitals [14], university campuses [15], and large urban office buildings [16].

Despite only 8% of the world's electricity being generated by CHP, Europe has embraced this technology and continues to promote installation of new plants in the residential sector. In Denmark, 52% of the electricity demand (5690 MW) is met by CHP, with most of the heat produced used for district heating systems, and more than half of Western Europe's CHP plants are connected to district heating and cooling systems [17].

While CHP appears to be economically feasible in a cold climate where heating is primarily used –as is the case in many European cities– the same may not be true for a hot climate. The climate, and consequently the location of the plant and the neighborhood to be supplied, has an effect on the electricity, heating, and cooling demands that need to be met. For example, in Sweden, the average summer temperature is between 55 °F and 63 °F [18], and this is reflected in typical energy use profiles (Fig. 2: Top); heating is still used in the summer. On the other hand, in the predominantly cooling climate typical for the Southwestern United States, there is little need for heating, and the energy use is dominated by cooling and electricity for lighting and appliances. Another key difference between heating and cooling climates is variability in energy demands: instead of the relatively constant demand profile of a house in a heating climate, the load profile in a cooling-dominant