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Econometric and Environmental Optimization of Combined Cooling, Heating and Power Plant Operation

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ABSTRACT

Combined Cooling, Heating and Power (CCHP) systems have great potential to recover low-grade thermal energy, resulting in higher energy efficiency, reduced emission rates, lower operating costs and a higher level of energy security. Effective optimization and control strategies are required to fully realize the benefits of CCHP systems in terms of reduced cost and carbon dioxide emissions. This work presents an approach for optimizing the operation of a campus CCHP system using a detailed network energy flow model solved by a genetic algorithm. The optimal energy dispatch algorithm provides operational signals associated with resource allocation ensuring that the systems meet campus electricity, heating, and cooling demands. The performance of the CCHP system is compared and evaluated in terms of economic and environmental benefits. This gives the decision maker more flexibility to examine and make clear judgement on the trade-offs involved between conflicting objectives for providing efficient and clean energy during the planning horizon. Example optimizations on cost and carbon dioxide emissions (CDE) were performed for a 24-hour period with known cooling, heating, and electricity demand on Purdue's main campus, and based on actual real time prices (RTP) for purchasing electricity. The results suggest there exists a potential cost savings up to 14% when optimized for cost, and emissions reduction up to 30% when optimized for CDE compared to the current CCHP operation. Sensitivity of the optimized results to the cost of purchased electricity and CO_2 emissions factor were performed to illustrate the operational switch between steam and electric driven components that occurs for optimal operation.

1. INTRODUCTION

Combined Cooling, Heating and Power (CCHP) systems, also known as trigeneration systems are very promising for distributed energy generation due to their higher energy conversion efficiency resulting in energy savings and consequent cost and emission reduction. These systems include different components relating to energy conversion, recovery and management with wide-ranging operational strategies to cater to multiple energy demands. It is very complex to effectively design optimal control strategies because of the stochastic behavior of energy loads and fuel prices, various component designs, diverse dynamic response characteristics at various time-scales, and operational limitations, as well as the mutual dependency of energy components. The potential benefits of CCHP systems can be assessed based on different aspects: 1) thermodynamics (maximum energy efficiency, minimum fuel consumption, minimum irreversibility), 2) economics (minimum operational cost), and 3) environmental (emissions reduction). Linear, nonlinear, mixed integer or evolutionary algorithms are used to find optimal solutions in terms of the above-mentioned aspects to control and operate CCHP systems. Several analyses have been performed on cost oriented optimization; however, they do not reflect the implications related to environmental effects.

Environmental economic dispatch could be treated as a single objective optimization problem by treating gas emissions as a constraint with a permissible limit or by expressing pollution damage costs due to the emissions (Ahmadi and Dincer, 2010), or by using weighted sum methods (Bracco *et al.* 2013). However, it becomes very difficult to interrelate several objectives of different natures properly, thereby making the objective function lose its significance (Deb, 2001). Few papers have been published on optimizing the energetic, economic, and environmental impact objectives simultaneously using multi objective models (Shi *et al.*, 2013 and Kavvadias and Maroulis, 2010). The interaction among different objectives gives rise to a set of compromised solutions, largely known as the trade-off, nondominated, noninferior or Pareto-optimal solutions. As a result, weights are applied by the decision maker to make a tradeoff between the criteria. The process is time consuming and sometimes, not all solutions are generated and important solutions can be overlooked in this method.

Genetic algorithms have provided effective approaches for solving CCHP optimization problems due to their ability to handle functions containing non-linearities and both discrete and continuous decision variables. A few papers have been published on optimizing the economic and environmental performances of CCHP systems using genetic algorithms with weighted sum methods (Wang *et al.*, 2010), and by the non-dominated Pareto-optimal approach (Guo *et al*., 2013). For most evolutionary algorithms, constraint handling becomes an important issue, where the methods used to handle the constraints always have a deep impact on the quality of the solutions obtained. A deterministic network flow model effectively illustrates the electric and thermal energy flows, energy supply and demand in the CCHP system and helps in building the constraints. Cho *et al.* (2009 & 2010) presented a network flow model for the optimization of a CCHP system based on operational cost, primary energy consumption and carbon dioxide emissions using linear programming.

A well operated CCHP system should balance economical savings as well as net emission of pollutants. This paper is an extension and improvement of Ramaraj *et al*. (2016) where the economic and environmental performances of the CCHP system at Purdue were analyzed and compared based on a cost optimization. In the current paper, the deterministic network energy flow model of the CCHP system was optimized based on both operational cost and carbon dioxide emissions using a genetic algorithm. The energy dispatch algorithm provides control signals to the operation of CCHP components in two levels: the outermost supervisory control determines the equipment to be operated based on the energy (thermal and electric) demand, and in turn, the inner layer of associated components (pumps, fans, cooling tower and other auxiliaries) are activated. Results from the simulation are presented in the paper to demonstrate how optimizing one parameter affects the other. This gives the decision maker more flexibility to examine and make a clear judgement on the trade-offs involved between conflicting objectives for providing efficient and clean energy during the planning horizon. An example optimization on cost and carbon dioxide emissions (CDE) was performed for a 24-hour period with known cooling, heating, and electricity demand for the campus, and based on actual real time prices (RTP) for purchasing electricity. Simulations are extended for different electric, heating and cooling load scenarios of Purdue's campus to examine the feasibility of the optimization algorithm for real-time operation. The sensitivity of the optimized results to purchased electricity cost and CO_2 emissions factor were analyzed to determine the operational switch between steam and electric driven components.

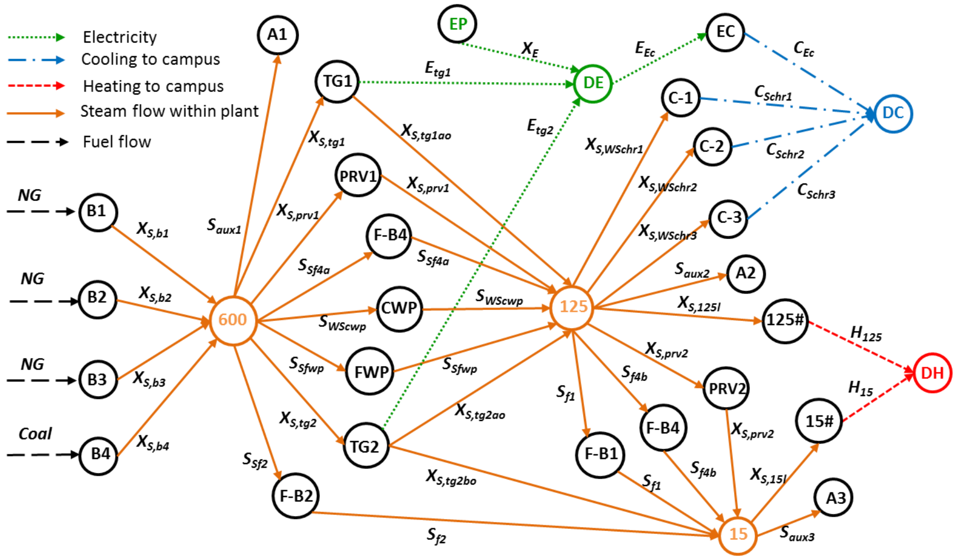
2. CONTROL STRATEGY AND OPTIMIZATION SCHEME

2.1 Energy Flow of CCHP system

In this study, the CCHP operation of the Wade power plant at Purdue University is considered. Detailed information on the energy flow and operation of the power plant is described in Ramaraj *et al*. (2016). The CCHP system contains separate components for heating, cooling and electricity production to meet the campus energy demand. The steam generated from three natural gas boilers and one coal boiler is used for campus heating, power generation, chilled water production and in-plant auxiliary component usage. High pressure steam from the boilers is extracted from a combination of turbines and pressure reducing valves at different pressure levels (600 psig, 125 psig and 15 psig) to run the necessary equipment and associated auxiliary components to produce adequate heating, cooling and power. Chilled water is produced using three steam driven chillers and a total of 10 electric chillers (four electric chillers at Wade power plant and six electric chillers at the Northwest Chiller plant). Electricity is generated using two steam turbine generators and the remainder is purchased from local electric utility to meet the campus electricity demand and to operate the other electric driven components within the power plant. Apart from these major components, there is other auxiliary equipment such as boiler fans, feed water pumps, chilled water pumps, system pumps and cooling tower fans and pumps that are activated depending on the major components to which they are linked. These auxiliary components are driven by steam or electricity or both.

2.2 Network Flow Model

A deterministic network flow model connecting the supply to demand was developed based on the energy flows of steam and electricity for the Purdue CCHP system (Ramaraj *et al*., 2016). The network flow model for the CCHP system is depicted in Figure 1. The network flow model illustrates the interactions between electric and thermal energy flows through the components and the nodes in this network represent sources of energy and energy demand points. Mass and energy conservation has been applied to develop the energy dispatch algorithm in conjunction with the network flow model. It can be seen that the demand drives the activation of individual components throughout the network. Control of the CCHP system is realized through a hierarchical paradigm. The outermost supervisory control layer determines which components should be operating (on/off states) depending on the fuel cost and electric, cooling, and heating energy demands, together with the energy flow and efficiency constraints of each component. Depending on the results of this outer layer, the inner layer of component controllers activates other auxiliary equipment associated with the major components in the CCHP system. The thermal and electrical demand of campus is met by the combination of all components in the plant.



Node B: Boilers
Node 600, 125, 15: 600, 125, 15 psig steam line
Node: A: Auxiliaries
Node TG: Turbine generators
Node F-B: Steam driven fan of the boiler
Node FWP: Steam driven feed water pumps
Node CWP: Steam driven chilled water pumps
Node PRV: Pressure reducing valve
Node EC: Electric chillers
Node C: Steam chillers
Node 125#, 15#: Steam line to campus
Node EP: Electricity purchased
Node DE, DC, DH: Electricity, Cooling, Heating demand

$X_{s,b}$: Steam from boilers
$X_{s,tg}$: Steam to turbine generators
$X_{s,tgo}$: Steam from turbine generators
$X_{s,prv}$: Steam from /to PRV
$X_{s,WSchr}$: Steam to steam chillers
$X_{s,125l}$: 125 psig steam to campus
$X_{s,15l}$: 15 psig steam to campus
X_E: Electricity purchased

E_{tg}: Electricity generated from turbine generators
E_{Ec}: Electricity to electric chillers
C_{Ec}: Cooling capacity from electric chillers
C_{Schr}: Cooling capacity from steam chillers
H: Heating capacity from 125/15 psig steam line
S_{Sf}: Steam from/to steam driven F-B
S_{Sfwp}: Steam from/to steam driven FWP
S_{Scwp}: Steam from/to steam driven CWP
S_{aux}: Steam to auxiliaries
NG: Natural Gas

Figure 1: Network energy flow model (Ramaraj *et al*., 2016).

2.3 Optimization framework

The network energy flow model described in the previous section facilitates setting up the objectives and constraints. Given the electrical and thermal (heating and cooling) load behavior of campus, the tariff structure for grid-supplied electricity, the price of primary fuel (e.g., natural gas & coal), the operating strategy and characteristics of the CCHP system, and an assumed set of installed CCHP system capacities (e.g., installed capacity of boilers, chillers and generators), operation of the CCHP plant in response to economic and environmental objectives can be analyzed. The nomenclature for optimization of the CCHP plant operation is defined in Table 1.

The first objective function is to minimize the operational cost of running the CCHP system while satisfying the total energy demand:

$$\text{Minimize} \qquad \mathrm{Cost}(x) = \sum_{i=1}^{3} c_{NG} * f_{NG} + c_C * f_C + c_E * x_{E,pur} \tag{1}$$

The objective function for the algorithm shown in equation (1) can be modified to minimize the amount of carbon dioxide emissions (CDE) as:

$$\text{Minimize} \qquad \mathrm{CDE}(x) = \sum_{i=1}^{3} e_{NG} * f_{NG} + e_C * f_C + e_E * x_{E,pur} \tag{2}$$

Here the fuel consumption of natural gas and coal are the functions of their respective boiler steam loads. Since carbon dioxide is the main emission from the system, and is the primary contributor to global warming, it is regarded as the objective function to be minimized.

Two types of constraints are considered in this problem, i.e. equality and inequality constraints. The former are the energy balance constraints while the latter constraints reflect the limits on heating, cooling and power generated by each unit. Equations (3)-(18) represent mass and energy balances across each node in Figure 1 and the impacts of those decisions on the supply of energy to meet the campus energy demands.

$$h(1) = x_{S,b1} + x_{S,b2} + x_{S,b3} + x_{S,b4} - x_{S,tg1} - x_{S,tg2} - s_{Sfwp} - s_{WScwp} - s_{Sf2} - s_{Sf4a} - x_{S,prv1} - s_{aux1} \tag{3}$$

$$h(2) = x_{S,tg1ao} + x_{S,tg2ao} + s_{Sfwp} + s_{WScwp} + s_{Sf4a} + x_{S,prv1} - x_{S,WSchr1} - x_{S,WSchr2} - x_{S,WSchr3} - s_{Sf1} - s_{Sf4b} - x_{S,prv2} - x_{S,125l} - s_{aux2} \tag{4}$$

$$h(3) = x_{S,tg2bo} + s_{Sf1} + s_{Sf2} + s_{Sf4b} + x_{S,prv2} - x_{S,15l} - s_{aux3} \tag{5}$$

$$h(4) = x_{W,Sfwp} + x_{W,\mathrm{E}fwp} - x_{S,b1} - x_{S,b2} - x_{S,b3} - x_{S,b4} \tag{6}$$

$$h(5) = x_{S,tg1} - x_{S,tg1ao} - x_{S,tg1bo} \tag{7}$$

$$h(6) = x_{S,tg2} - x_{S,tg2ao} - x_{S,tg2bo} \tag{8}$$

$$\begin{aligned} h(7) = {} & x_{S,b1} * h_{b1} + x_{S,b2} * h_{b2} + x_{S,b3} * h_{b3} + x_{S,b4} * h_{b4} \\ & -\left(x_{S,b1} + x_{S,b2} + x_{S,b3} + x_{S,b4}\right) * h_{600} \end{aligned} \tag{9}$$

$$\begin{aligned} h(8) = {} & x_{S,tg1ao} * h_{tg1ao} + x_{S,tg2ao} * h_{tg2ao} + s_{Sfwp} * h_{Sfwp} + s_{WScwp} * h_{WScwp} + s_{Sf4a} * h_{Sf4a} \\ & + x_{S,prv1} * h_{prv1} - \left(x_{S,tg1ao} + x_{S,tg2ao} + s_{Sfwp} + s_{WScwp} + s_{Sf4a} + x_{S,prv1}\right) * h_{125} \end{aligned} \tag{10}$$

$$\begin{aligned} h(9) = {} & x_{S,tg2bo} * h_{tg2bo} + s_{Sf1} * h_{Sf1} + s_{Sf2} * h_{Sf2} + s_{Sf4b} * h_{Sf4b} + x_{S,prv2} * h_{prv2} \\ & -\left(x_{S,tg2bo} + s_{Sf1} + s_{Sf2} + s_{Sf4b} + x_{S,prv2}\right) * h_{15} \end{aligned} \tag{11}$$

$$h(10) = D_{h,125l} - H_{125} \tag{12}$$

$$h(11) = D_{h,15l} - H_{15} \tag{13}$$

$$h(12) = D_c - C_{Schr1} - C_{Schr2} - C_{Schr3} - C_{Echr} \tag{14}$$

$$h(13) = D_e - x_{E,pur} - E_{tg1} - E_{tg2} \tag{15}$$

where,

$$H_{125} = \Delta h_{125l} * x_{S,125l}\,; \quad H_{15} = \Delta h_{15l} * x_{S,15l} \tag{16}$$

$$C_{Schr} = \sum_{i=1}^{3} cop_{Schr} * x_{S,WSchr} * \Delta h_{WSchr}\,; C_{Echr} = cop_{Echr} * x_{\mathrm{E},WEchr} + cop_{Echr} * x_{\mathrm{E},NWEchr} \tag{17}$$

$$E_{tg1} = \eta_{tg,1} * \Delta h_{\mathrm{tg1a}} * x_{S,tg1} + \eta_{tg,1} * \Delta h_{\mathrm{tg1b}} * x_{S,tg1bo}\,; \quad E_{tg2} = \eta_{tg,2} * \Delta h_{\mathrm{tg}2a} * x_{S,tg2} + \eta_{tg,2} * \Delta h_{\mathrm{tg2b}} * x_{S,tg2bo} \tag{18}$$

Additional inequality constraints deal with peak capacity limitations of the components. The characteristic curves of all the components were determined from power plant operational data and/or manufacturer's data. Lower and upper bounds on the decision variables are given as inputs to the model. Table 1 gives the list of decision variables and parameters used in this energy dispatch algorithm. The CCHP model is complex and involves 22 design variables with 13 equality constraints and 14 inequality constraints. This optimization problem has a non-linear objective function with linear and nonlinear, equality and inequality constraints and strong coupling to the three energy demand components (electricity, heating and cooling). Some of the design variables are continuous while others are discrete. Because of the multimodal and discontinuous nature of this problem, a genetic algorithm (GA) was chosen as the solution methodology. Detailed explanation of the constrains and implementation of the genetic algorithm along with the energy dispatch algorithm is illustrated in Ramaraj *et al*. (2016).

Table 1: Decision variables and other parameters

Decision variables		**Parameters**			
$x_{E,NWEchr}$	Electricity to North West electric chillers (kW)	c_C	Fuel cost of Coal ($/ST)	f_C	Amount of Coal consumed (ST)
$x_{E,pur}$	Electricity purchased from utility (kW)	c_E	Cost of electricity purchased ($/kWh)	f_{NG}	Amount of Natural Gas consumed (DTH)
$x_{E,WEchr}$	Electricity to Wade electric chillers (kW)	c_{NG}	Fuel cost of Natural Gas ($/DTH)	H_{125}	Amount of heating provided by 125 psig steam (kW)
$x_{S,b}$	Steam output from each boiler (kg/s)	C_{Echr}	Cooling capacity from electric chillers (kW)	H_{15}	Amount of heating provided by 15 psig steam (kW)
$x_{S,125l}$	125psig Steam output to campus (kg/s)	C_{Schr}	Cooling capacity from steam chillers (kW)	h	Enthalpy (kJ/kg)
$x_{S,15l}$	15psig Steam output to campus (kg/s)	cop_{Echr}	Coefficient of performance of electric chillers (-)	Δh_{tg}	Enthalpy change across turbine generator (kJ/kg)
$x_{S,prv}$	Steam input to pressure reducing valve (kg/s)	cop_{Schr}	Coefficient of performance of steam chillers (-)	Δh_{WSchr}	Enthalpy change across turbine of steam chillers (kJ/kg)
$x_{S,tg}$	Steam input to turbine generator (kg/s)	D_c	Cooling Demand (kW)	Δh_{125l}	Enthalpy change across 125 psig steam line (kJ/kg)
$x_{S,tgao}$	Steam output from stage 1 of turbine generator (kg/s)	D_e	Electricity Demand (kW)	Δh_{15l}	Enthalpy change across 15 psig steam line (kJ/kg)
$x_{S,tgbo}$	Steam output from stage 2 of turbine generator (kg/s)	D_h	Heating Demand (kW)	s_{aux}	Steam input to auxiliaries (kg/s)
$x_{S,WSchr}$	Steam input to Wade steam chillers (kg/s)	e_C	Emissions factor of Coal (metric tons CO_2/ST)	s_{Scwp}	Steam input to steam-driven chilled water pump (kg/s)
$x_{W,E\,fwp}$	Water input to electric feedwater pump (kg/s)	e_E	Emissions factor of electricity purchased (metric tons CO_2/kWh)	s_{Sf}	Steam input to steam-driven fan (kg/s)
$x_{W,Sfwp}$	Water input to steam-driven feedwater pump (kg/s)	e_{NG}	Emissions factor of Natural Gas (metric tons CO_2/DTH)	s_{Sfwp}	Steam input to steam-driven feedwater pump (kg/s)
		E_{tg}	Electricity generated by turbine generator (kW)	η_{tg}	Turbine generator efficiency (-)

2.4 Data required and assumptions for the model

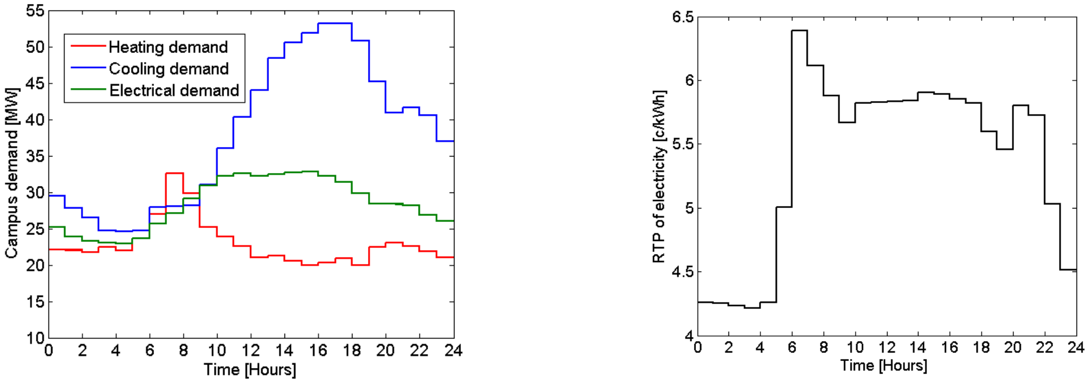
Data required for the CCHP cost and carbon dioxide emissions optimizations and performance evaluations that were available from Purdue Physical Facilities for this study are listed as follows:

- Hourly load (demand) data of Purdue campus for electricity, heating, and cooling
  - End-use loads vary by application type, building size, location, season, work week, and hour
- Utility electricity prices
- Price of on-site fuel (e.g., natural gas, coal)
- CO_2 emission factors for natural gas, coal and purchased electricity
- Range of “effective” operation of CCHP components for a given installed capacity

3. SIMULATION RESULTS

3.1 Single day simulation results

An example optimization was performed for a 24-hour period with known cooling, heating, and electricity demand for the campus, and based on actual real time prices (RTP) for purchasing electricity. An hourly interval is assumed and no dynamics are considered in the plant modeling. Figure 2(a) represents thermal and electrical demand and Figure 2(b) shows the real-time price of electricity on Wednesday, 20th April, 2016. The price of natural gas is assumed to be 3.00 $/DTH and the cost of coal is 70.80 $/ST, which includes the cost of limestone, ash handling and so on. The CO_2 emission factor for circulating fluidized bed coal is 2.33 metric tons CO_2/ST and for natural gas is 0.053 metric tons CO_2 /DTH (U.S. Environmental Protection Agency, 2015). For Indiana, the emission factor for purchased electricity is 0.00089 metric tons CO_2/kWh (85% of electricity is from coal, 8% from natural gas and 7% from other sources) and 6% transmission and distribution losses are considered (U.S. Energy Information Administration, 2018). These details were provided as inputs to the 24-hour model to compare the optimal performance with respect to cost and CDE with the actual operation of the plant.



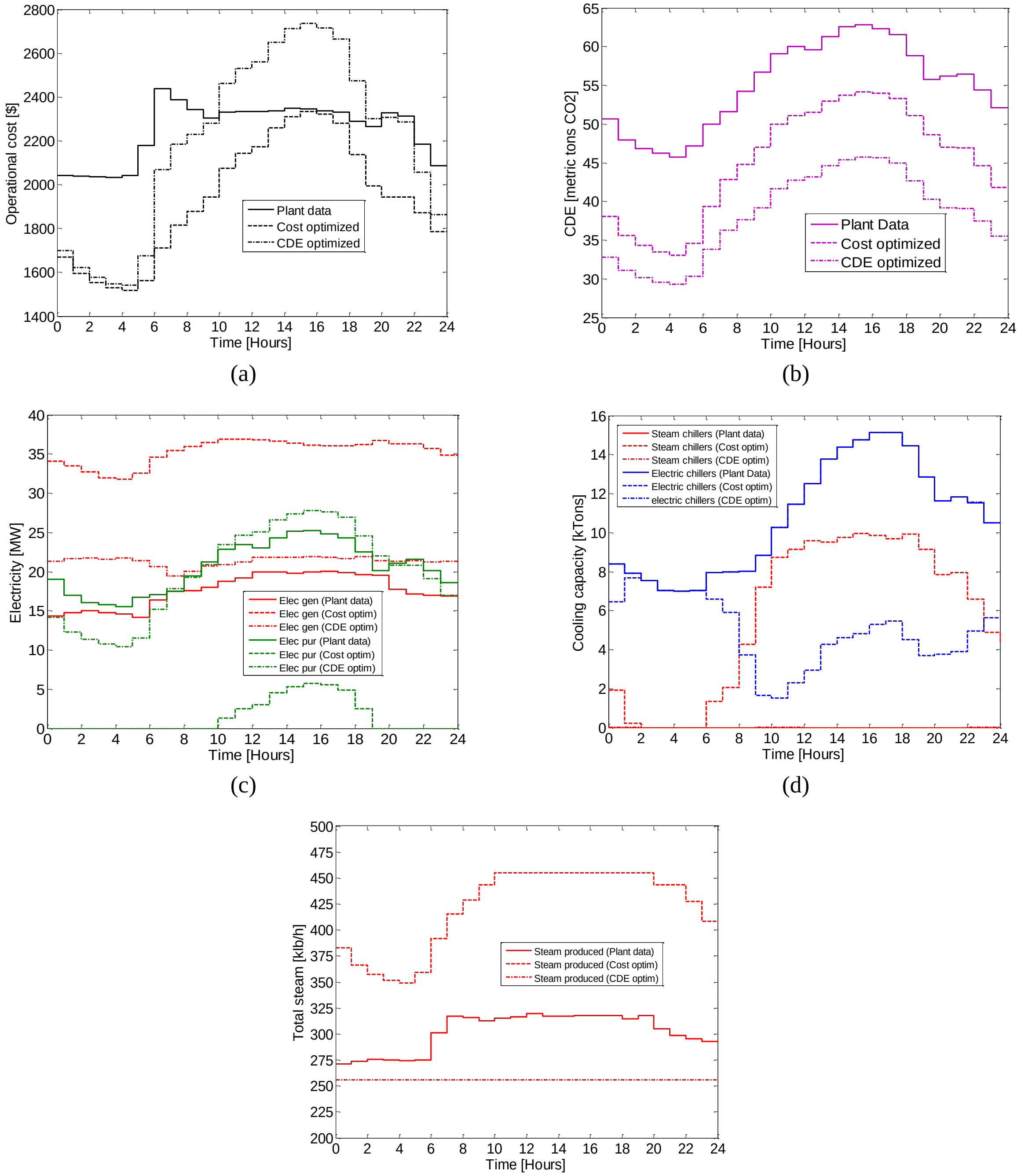
(a) (b)

Figure 2(a): Energy demand of Purdue campus; **(b):** Real time electricity price.

Figure 3 compares the cost optimization and CDE optimization results with results determined using the end-use decisions from the actual plant data (e.g., electricity produced, electricity purchased, steam produced in each boiler, chilled water from electric chiller, chilled water from steam chillers) as inputs to the model to estimate total operational cost and CO_2 emissions for the current control. From Figure 3(a), it can be seen that the total operational cost is significantly less for cost optimized control compared to current practices or CDE optimized control for most hours of the day. It is also interesting to note that carbon dioxide emissions for cost optimized control are significant lower than current practice, as shown in Figure 3(b). However, these results also show that significantly greater reductions in emissions are possible when employing CDE optimization. Figure 3(c) shows comparisons of electricity produced and purchased for the actual operation with the cost and CDE optimum results. The optimum results predict that more electricity should be generated compared to the actual operation to meet the total electrical demand. However, the optimum still leads to purchasing of some electricity during peak hours of the day. Figure 3(d) shows comparisons of cooling capacity produced by steam chillers and electric chillers. In the actual operation and CDE optimization, all the campus cooling demand was satisfied with the electric chillers. The cost optimum results predict the usage of both electric and steam chillers to meet the campus cooling load especially when the demand is high. Figure 3(e) shows the total amount of steam produced in the boilers for the actual operation and optimal results. It can be seen that more steam is produced in cost optimized operation with the additional steam used for both operation of turbine generators to generate more electricity and steam chillers. In the actual plant operation and CDE optimization, only two natural gas boilers were used, whereas the optimized results include the usage of a coal boiler along with the two natural gas boilers. The selection between coal and natural gas boilers depends on fuel cost, emissions factor, boiler efficiencies and their operating conditions which play a major role in assessing the economic and environmental benefits. The less steam production for CDE optimum contributes to more operational cost especially when the cooling demand is high. Table 2 gives a summary of comparisons between actual plant operation (reference data) and two optimized results for this 24-hour period. Cost optimization resulted in about 14% cost savings while CDE optimization led to almost 11% cost savings compared to the actual performance. The carbon dioxide emissions are reduced by about 18% when optimized for cost and 30% when optimized for CDE.

Table 2: Comparison between current operation and optimized results

For 24 Hours	Plant data	Cost Optimized	CDE Optimized
Total steam produced [klb]	7254	10120	6145
Total electricity generated [MWh]	422	847	512
Total electricity purchased [MWh]	492	35	477
Cooling from steam chillers [kTon-h]	0	139	0
Cooling from electric chillers [kTon-h]	258	118	258
Total cost of operation [$]	54006	46341	52739
Total cost savings [$]		**7665 [14.19%]**	**1266 [2.34%]**
Total CDE [metric tons CO_2]	1320	1084	918
Total CDE reduction [metric tons CO_2]		**237 [17.91%]**	**402 [30.45%]**



(a) (b) (c) (d) (e)

Figure 3: (a) Total operational cost; **(b)** Total carbon dioxide emissions; **(c):** Amount of electricity generated and purchased; **(d)** Cooling capacity of steam and electric chillers; **(e)** Total steam produced in boilers

3.2 Sensitivity to energy demand

Simulations were performed to examine the sensitivity of the optimization results to differences in electric, heating and cooling demand. Variations in the energy load are primarily due to seasonal variations which depend on ambient temperature and worker/student schedules due to day and school session type (e.g., weekends, weekdays, holidays, semester, semester break, summer school, Maymester, etc). Three energy demand scenarios of Purdue's campus for a particular peak hour during weekdays were considered for this case study [Case 1: high cooling load (summer), case 2: high heating load (winter), and case 3: high electrical demand (fall)] as shown in Table 3. The values specified in the previous section were employed for the price of natural gas, coal and CO_2 emissions factor for natural gas, coal and purchased electricity. However, the cost of purchased electricity was set as 4.50 ¢/kWh.

Table 3: Purdue campus energy demand scenarios

	Season	**School session type**	**Date**	**Outdoor air temperature (°F)**	**Cooling Load** kW (Tons)	**Heating Load** kW (MMBtu/h)	**Electrical Load** kW
Case 1	Summer	Weekday	08/30/2016	86	89354(25385)	28310(97)	29406
Case 2	Winter	Weekday	01/27/2016	26	22049(6264)	75056(256)	25495
Case 3	Fall	Weekday	10/17/2016	75	55450(15752)	34040(116)	32432

Optimization results were obtained using the two different objective functions for operational cost and CDE and are presented in Table 4. For the three cases considered, the total operational cost using cost optimization is 3%-5% lower compared to CDE optimization while the total carbon dioxide emissions using CDE optimization is 13%-15% lesser compared to the values from cost optimization. When the objective is cost minimization, most electricity is generated onsite to meet the electrical demand and hence, more steam is produced. The mutual dependency of electricity and steam production from the turbine generator has a limit on the electricity generated when the heating demand is met. The rest of the electricity is purchased in this case. However, when the objective function is with respect to CDE, use of the coal boiler is avoided and electricity is purchased to meet electrical demand. Also, it is interesting to observe that more cost and emissions reduction is possible with case 2 where the heating demand is higher. This is mainly because of the maximum usage of natural gas boilers to meet the high heating demand.

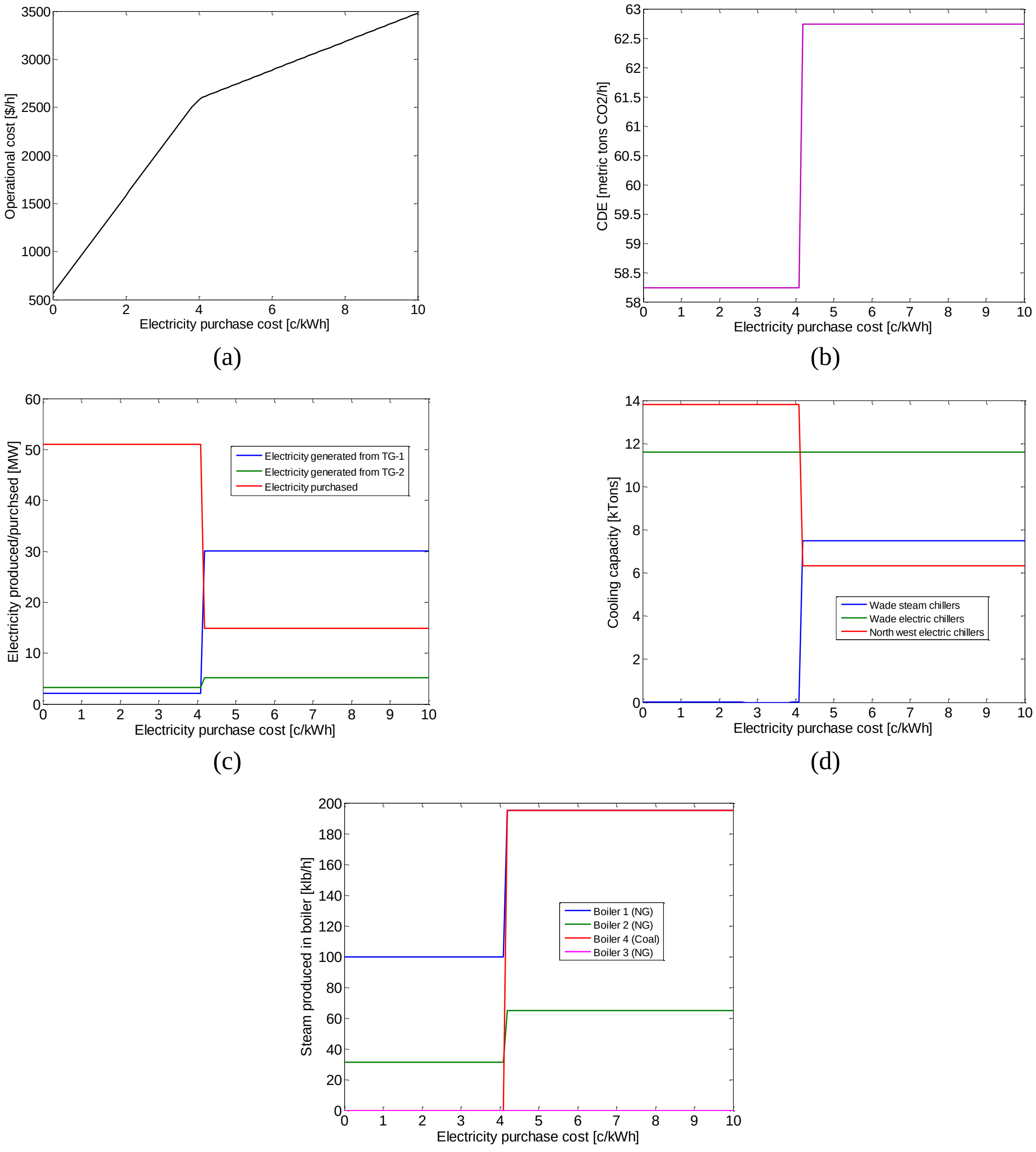
Table 4: Simulation results for different energy demand

	Total operational cost [$]			**Carbon dioxide emissions** [metric tons CO_2]		
	Cost Optim.	CDE Optim.	% Difference	Cost Optim.	CDE Optim.	% Difference
Case 1	2663.59	2760.39	3.51%	62.74	54.43	13.25%
Case 2	2063.97	2162.40	4.55%	50.11	42.56	15.07%
Case 3	2408.38	2507.24	3.94%	57.37	49.10	14.42%

3.3 Sensitivity to fuel price and carbon dioxide emissions factor

The primary energy usage of the CCHP plant depends on the decisions regarding generation and/or purchasing of electricity in response to minimizing operational costs or CO_2 emissions while also meeting the time-varying campus electricity, heating and cooling demands. The sensitivity of the predicted results to the cost of purchased electricity and CO_2 emissions factor were studied and typical results are presented in this section. The campus energy demand for a particular hour of a summer day was used for the sensitivity analysis, where the heating demand, D_h, was 97MMBtu (28,310 kW), cooling demand, D_c, was 25,385Tons (89,354 kW) and the electrical demand, D_e, was 29,406 kW. The cost of coal was set as 70.80 ($/ST) and the cost of natural gas was set as 3.00 ($/DTH) for the analysis. The CO_2 emission factor for coal was 2.33 metric tons CO_2/ST and for natural gas was 0.053 metric tons CO2 /DTH.

For studying the effect of electricity prices, the cost of purchased electricity was varied from 0 to 10 (¢/kWh) while the emission factor was set as 0.00089 metric tons CO_2/kWh. Figure 4 shows the cost optimization results for varying the cost of purchased electricity. Figure 4(a) shows that the total operational cost of the plant increases monotonically when the price of electricity increases. This is because some amount of electricity is purchased apart from generation in order to meet the total electrical demand, while satisfying the thermal demand of campus. When rates are above 4.20 ¢/kWh, there is an increase in the carbon dioxide emissions as shown in Figure 4(b). This is because more steam is produced from the coal boiler. The selection of the coal boiler over one of the natural gas boilers is because of its efficiency and operational conditions. Figure 4(c) shows comparisons of electricity generated and purchased for the varying cost of electricity. It can be seen that a higher quantity of electricity is purchased at lower costs of electricity. As the price of electricity increases above 4.20 ¢/kWh, there is a reduction in the purchase of electricity and an increase in the generation of electricity from the turbine generator 1 (TG-1). However, some amount of electricity is purchased during the day to meet the electrical demand of campus and all electricity cannot be generated because of limited availability of steam for TG-1 due to a low campus heating demand. Figure 4(d) shows comparisons of cooling capacity produced by steam chillers and electric chillers over the range of electricity rates. The control switches from maximizing electric chiller operation at low rates, to using steam chillers when rates are above 4.20 ¢/kWh in order to meet the campus cooling demand. However, Wade electric chillers are operated on this summer day due to a high cooling demand. From Figure 4(e), we can see that as the price of electricity increases, more steam is produced to meet the steam demand of the turbine generators and steam chillers. At lower electricity prices, some amount of steam is still produced to meet the campus heating demand. Boilers 1, 2 and 3 are natural gas boilers while boiler 4 is a coal boiler. The boilers are brought online depending upon their efficiency at different steam loads and operating conditions. Since it is obvious that the energy pricing affects only the economic objective function, a CDE-based optimization was not included in this sensitivity study.



(a)

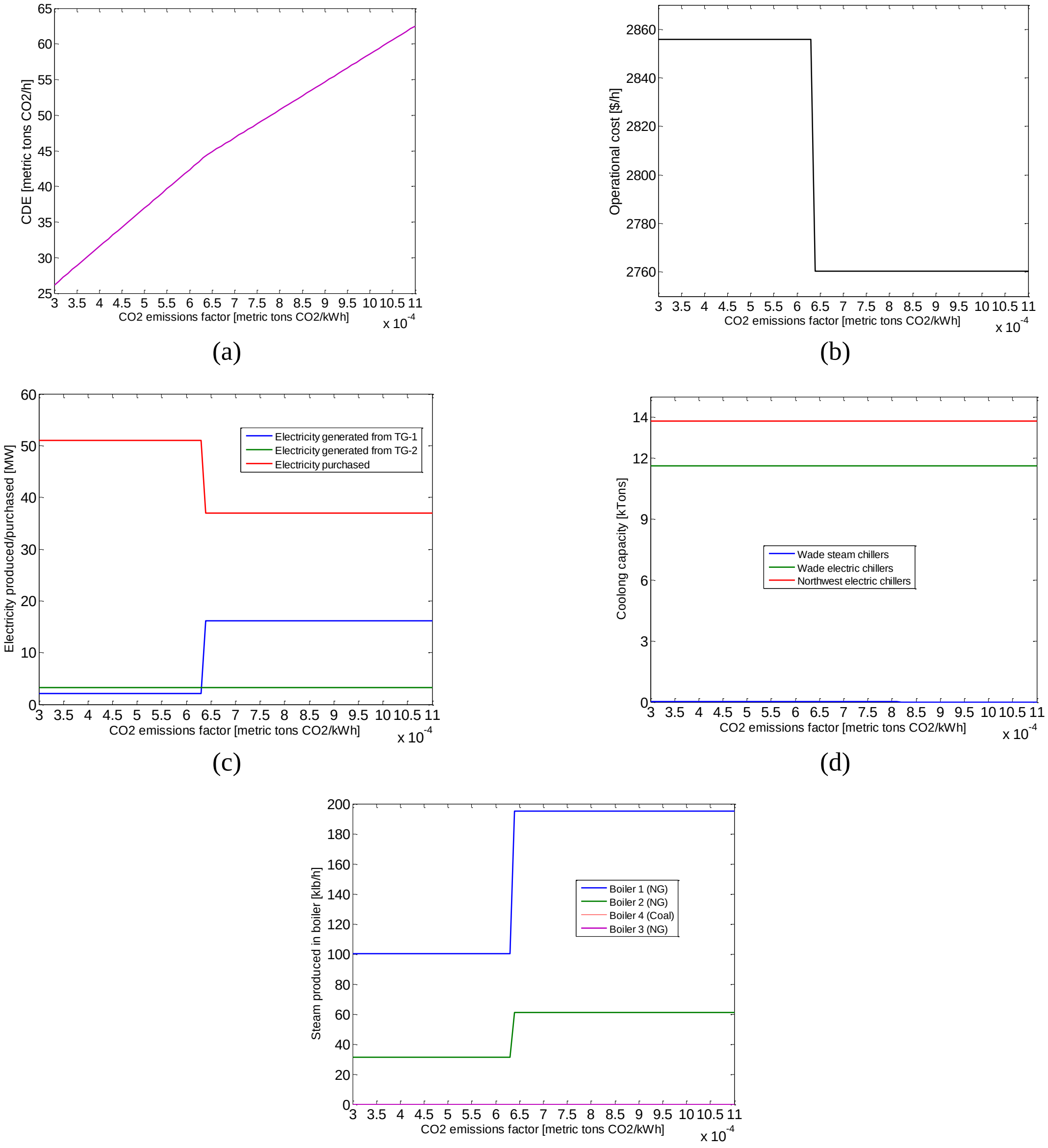
(b)

(c)

(d)

(e)

Figure 4: Cost optimization results for individual hour with varied electricity purchase cost: **(a)** Total operational cost; **(b)** Total carbon dioxide emissions; **(c):** Amount of electricity generated and purchased; **(d)** Cooling capacity of steam and electric chillers; **(e)** Total steam produced in boilers



(a) (b)

(c) (d)

(e)

Figure 5: CDE optimization results for varied CO_2 emissions factor of purchased electricity: **(a)** Total carbon dioxide emissions; **(b)** Total operational cost; **(c):** Amount of electricity generated and purchased; **(d)** Cooling capacity of steam and electric chillers; **(e)** Total steam produced in boilers

However, the variation in CO_2 emissions factors due the mix of electricity from various sources affects the CDE objective. Indiana has a major contribution of electricity from coal power plants. The mix of electricity varies according to the fuel source (coal, natural gas, petroleum, nuclear, renewables and other sources) which affects its CO_2 emissions factor. For states like California and Massachusetts, the CO_2 emissions factor for electricity is as low as 0.0004 metric tons CO_2/kWh (U.S. Energy Information Administration, 2018). So, for a second case study, the CO_2 emissions factor for electricity was varied from 0.0003 to 0.0011 metric tons CO_2/kWh and the cost of electricity was set as 4.50 ¢/kWh. Figure 5 shows CDE optimization results for varied CO_2 emissions factors of purchased electricity. Figure 5(a) shows that the total CDE of the plant increases monotonically when the CO_2 emissions factor increases. This is because of the contribution from purchased electricity. When the emissions factor is above 0.00064 metric tons CO_2/kWh, there is a decrease in the operational cost of the power plant as shown in Figure 5(b). This is because of the reduction in electricity purchase as shown in Figure 5(c) and more steam generation as depicted in Figure 5(e). Figure 5(d) shows that the CO_2 emissions factor doesn't affect the performance of the chillers to meet the campus cooling demand and electrical chillers are run all the time. The restriction on running the steam chillers is due to the limitation on the turbine generator to extract steam to meet campus heating demand. Only natural gas boilers are run due to the high carbon dioxide emissions from the coal boiler. The reduction in emissions strongly depends on the total energy consumption and the emission conversion factor. The sensitivity analysis gives an idea about how the cost and emission factors drive the operational switch between steam and electric driven components.

5. CONCLUSION

A non-linear genetic algorithm (GA) was applied to a detailed network energy flow model of a large CCHP system in order to evaluate the economic and environmental benefits of optimal operation. The optimal energy dispatch algorithm provides operational signals associated with resource allocation ensuring that the systems meet campus electricity, heating, and cooling demands. Example optimizations for cost and carbon dioxide emissions (CDE) were performed for a 24-hour period with known cooling, heating, and electricity demand of Purdue's campus, and based on actual real time prices (RTP) for purchasing electricity. The results suggest that there is a potential to achieve cost savings up to 14% when optimized for cost, and emissions reduction up to 30% when optimized for CDE compared to the current CCHP operation. A sensitivity analysis on the cost of purchased electricity and CO_2 emissions factor demonstrates the opportunity to make operational decisions and switch between the use of steam-driven and electricity-driven components. This analysis gives the decision maker more flexibility to examine the optimal results and make a clear judgement on the trade-offs involved between conflicting cost savings and CDE reduction objectives for efficient and clean provision of energy during a planning horizon. Future work will focus on developing practical implementation approaches.

NOMENCLATURE

c	cost	($)
C	Cooling capacity of chillers	(kW)
CCHP	Combined Cooling, Heating and Power	
CDE	Carbon Dioxide Emissions	
CO_2	Carbon dioxide	
cop	Coefficient of performance	(–)
D	Energy demand	(kW)
DTH	Dekatherm	
e	Emissions factor	(metric tons CO_2)
f	Amount of fuel consumed	(ST/DTH)
H	Amount of heating provided	(kW)
h	Enthalpy	(kJ/kg)
s	Steam input	(kg/s)
ST	Short Ton	
x	Decision variables	
η	Efficiency	(-)

Subscript

C	Coal
c	Cooling
chr	Chiller
e	Electricity/electric
E	Electricity/electric
NG	Natural Gas
S	Steam
tg	Turbine generator
W	Water/Wade
125	125 psig steam line
15	15 psig steam line

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