An Energy Management System for Building Structures Using a Multi-Agent Decision-Making Control Methodology

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***Abstract*—Aligned towards net zero energy building goals, building energy management systems will consider energy utilization efficiency improvement, energy cost reduction and renewable energy technology utilization to serve the local energy loads in building structures with dispersed resources. The distributed management of building energy system in this paper describes a semi-centralized decision making methodology using multi-agent systems for building energy management system in electrical, heating and cooling energy zones with combined heat and power system optimization aimed at improving energy efficiency and reducing energy cost. The semi-centralized decision making process will be implemented in a case study to pursue minimum energy cost.**

***Keywords*-cyber-physical systems, building energy management systems, multi-agent systems, net-zero energy buildings, distributed generation.**

I. INTRODUCTION

With concerns of increasing green house gas (GHG) emissions and prices of fossil fuels, renewable energy sources (RES), distributed generation (DG), energy storage, and Smart Grid technology are poised to attract unprecedented attention. It is expected that evolving energy systems may be more distributed in nature than the legacy versions, with most of the changes being implemented on the consumer side. This is based on the fact that the US electricity grid is seeing steadily increasing projections of supply and demand growth for the next two decades while the trend in transmission systems indicate steady disinvestments and generally restrictive regulatory barriers for new transmission lines [1]-[2]. Thus, the management and control of a highly distributed energy system at the consumer end might present an urgent issue for exploration. Due to the limited capabilities of centralized computing on large-scale distributed systems, decentralized or semi-centralized decision-making process is viewed as a suitable option for employment in distributed energy systems. A possible approach to the solution of managing distributed energy systems is through the use of multi-agent systems (MAS).

MAS is an aggregation of networked agents, or controllers, for achieving some global objectives by coordination and communication among the agents [3]. This paper discusses the applicability of a MAS based control methodology for a model of building energy management system (BEMS), an example of a distributed energy system, given in [4].

Building structures in the U.S. consume significant levels of energy, particularly electricity, and emit GHG [5]. Reference [4] proposes a BEMS framework for addressing energy management in buildings with the assumed objectives of increased energy efficiency, decreased cost of energy, decreased dependence on use of fossil fuel for energy needs and consequently decreased GHG emissions. The definition of "*net zero energy costs*" for zero energy buildings (ZEB) given in [5] is used to set an optimization goal for the MAS-based BEMS described in this paper.

The rest of this paper is organized as follows: Section II describes the system organization of BEMS; Section III presents the decision making agents in three energy zones; Section IV presents a case study for achieving minimum energy cost.

II. SYSTEM STRUCTURES OF BUILDING ENERGY MANAGEMENT SYSTEM

A. Commercial Building Energy System

In a typical commercial building, the energy consumption at the end use is showed as below:

As shown in Fig. 1, the heating, ventilating and air-conditioning (HVAC) system consumes more than 50%

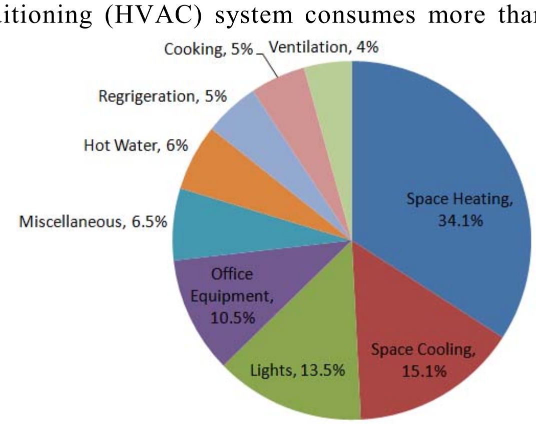

Fig. 1. The commercial building energy use [6]

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energy of a typical commercial building, when combined with the hot water needs, the energy consumption in the heating and cooling energy zones is 60%. Lighting and office equipment are the biggest two electric consumers, which constitutes more than 20% of the commercial building energy demand. Towards energy efficient and even net-zero energy building (NZEB) goals, [5], energy saving techniques such as passive solar heating, passive cooling, natural ventilation, natural day lighting, LED light bulbs, and “Energy Star” certified appliances, etc. are being pursued in the energy efficient building industry. The cyber enabled building energy management system (CEBEMS) based on the conceptual framework given in [4] will be discussed in detail in the following sections. The CEBEMS was described in [4] with particular focus on a) the physical aspects, including some novel hardware, and b) the cyber aspects, including energy management schemes of heating, cooling and electrical energy zones.

B. *Physical Aspect of CEBEMS*

Fig. 2 shows the building energy generation and storage and consumption units and the energy flow paths. The objective of such a system is to achieve high overall energy efficiency, low emissions and economic feasibility, without compromising the preferences and comfort of consumers.

The proposed local BEMS has three zones of interest—the electrical zone, the heating zone, and the cooling zone. The electrical zone may possess some RES. In this formulation, a photovoltaic (PV) resource, grid connection, and combined heat and power (CHP) units are used as generation units and an energy storage unit (e.g. battery bank) is present in the system. This setup is responsible for powering the electrical loads in the building. The heating zone possesses a solar-thermal heater, recovered heat from CHP units, a natural gas furnace and thermal storage as heat generation and storage units. The heating loads may be divided according to space heating and hot water needs. The cooling zone may possess an air-conditioning unit and an absorption chiller that uses the recovered heat from CHP to provide space-cooling needs. It is expected that not all the blocks shown in Fig. 1. need to be employed in a candidate CEBEMS. The selection and combination of the appropriate blocks depends on the building size and energy needs. In commercial buildings, on-site electric generator combined with waste heat recovery and absorption chillers are called building cooling, heating and power (BCHP) system, [7][7], where the waste heat from generator is utilized for both building heating and cooling. Typically the fuel utilization efficiency BCHP system is around 80%, some systems may exceed 90%, [8], which is much higher than the maximum efficiency for delivered power of a central power plant (i.e., 55% - 60%), [8]; when the carbon savings of BCHP system is compared with a traditional boiler and chiller system, the result is significant [7]. Commercial buildings can also employ solar thermal panels for domestic hot water (DHW), and solid oxide fuel cell (SOFC) in the CCHP system as clean and renewable energy sources for the purpose of GHG reduction and fossil fuel independence.

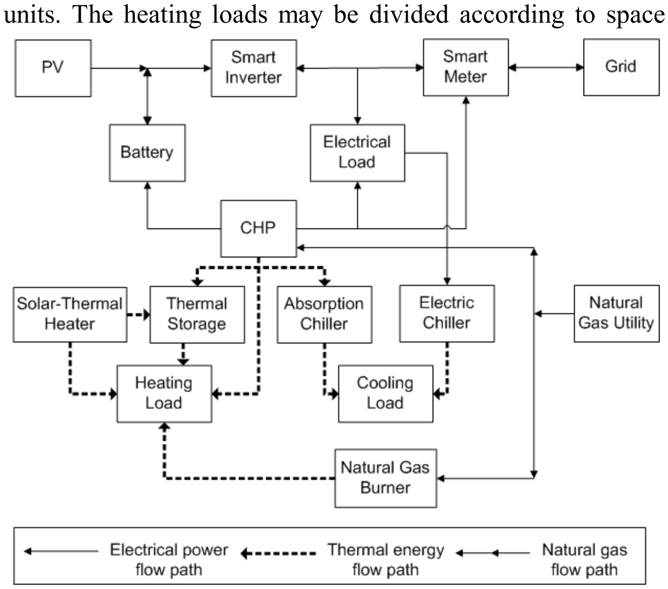

Fig. 2. The physical part of BEMS [4].

C. *Cyber Aspect of CEBEMS*

The proposed CEBEMS is achieved by a MAS approach as shown in Fig. 3. In each zone identified in Section II.A, the energy conversion, storage and consumption are precisely measured and dispatched by the intelligent agent embedded in each zone. The respective agents are the E-agent for electricity, the H-agent for heating, and the C-agent for cooling zones, respectively. The three agents communicate with each other through local area network (LAN) when the energy management task is beyond the capability of a single agent, or the agents are required to work together for a series of tasks. The energy management and control methods of three agents and their communication are discussed in detail in section III.

III. Decision Making Process for Multi-agent System

In a commercial BCHP system, the energy system sizing for electrical, heating and cooling zones is very important, because when the on-site generation is working, the recovered waste heat should also be utilized simultaneously, otherwise, the overall energy efficiency will go down, and its advantage of energy efficiency and cost effectiveness will be lost. The system sizing basically has three comparative references: *a)* tracking electrical load, *b)* providing electrical base load, and *c)* following thermal load. The comparative reference a) is most likely designed for a building islanded from the grid, so the building can be energy independent. Due to the fuel cost, on-site generator maintenance cost, and time of use (TOU) electricity rate, reference *a)* is not cost effective for buildings connected with the grid. Reference *b)* is designed for a grid

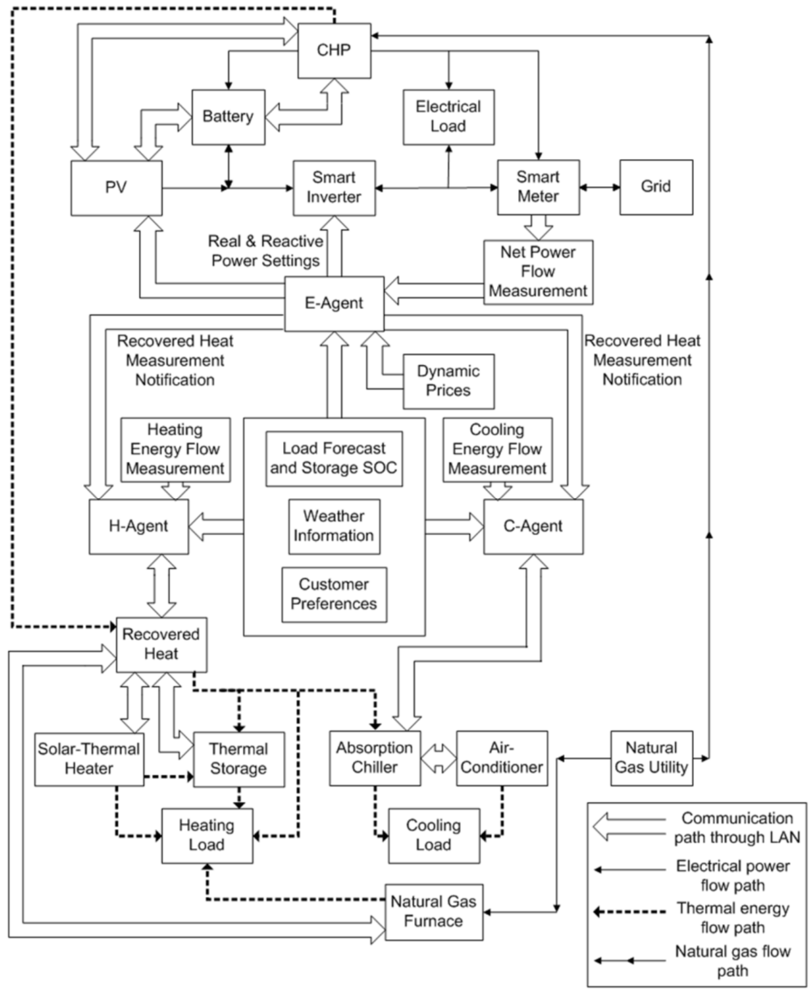

Fig. 3. The building energy management system through a multi-agent system approach [4].

connected building, so the surplus electricity generated during off-peak hours can be sold back to the grid to offset the electricity purchased during on-peak hours. However, the thermal demand is likely higher during the day and dropping to a lower value during the night; this may lead to the thermal energy output being over generated during the night and under generated during the day. This will result in the surplus thermal energy wasted during the night, and the unmet thermal load during the day must be satisfied by a supplemental boiler, which will possibly result in extra installation cost, more energy cost, and the loss of BCHP system benefits. A possible recommendation is to size the BCHP system based on comparative reference *c)*, i.e., to follow thermal load. The generator is viewed as a boiler to provide hot water for building heating and also a heat source of absorption chiller for building cooling demand. The electricity generation is viewed as an additional component, which can at least offset some level of demand, and any surplus will be sold back to grid for profit. As shown in Fig. 1, the thermal load is higher than electric load in a typical commercial building, so sizing and scheduling the BCHP system based on comparative reference c) may provide high energy utilization efficiency of BEMS, which will be examined in the case study shown in section IV. The purpose of comparative reference *c)* is to fully utilize the BCHP system in BEMS.

A. Energy Mangement in the Heating Zone—The Decision Making Control of H-Agent

The BCHP system in the proposed commercial office building is sized based on the heating load, where the H-Agent is responsible for fully utilizing the recovered heat for heating. However, the space heating demand in each room of the building may not be accurately predicted, so a boiler is needed as heating supplement.

The goal of the CEBEMS is to minimize the energy cost, so the real energy cost in each zone must be examined before any optimization technique is implemented for “minimized cost”. In the heating zone, the possible energy cost comes from the generation and distribution side of hot water. Hot water recovered from generator is viewed as byproduct of electricity generation, so the fuel cost is already counted in electrical zone, and this part of hot water is viewed as free of charge in heating zone. Hot water produced from the supplemental boiler needs natural gas as fuel, so this cost should be counted in the heating zone. On the distribution side, no matter if the hot water is heated up by natural gas a boiler or recovered waste heat of a generator, water pumps need to be working all the time regardless of the hot water sources. The electricity consumption is also counted in the electrical zone, so the hot water distribution is viewed as free of charge in the heating zone. Therefore, the minimum energy cost of a day in the heating zone can be shown as (1), where the energy consumption is examined every 15 minutes, and then the sum of the money spent in these time intervals will be the cost for one day.

$$\min \sum_{t=0}^{24\times 4} (\$NG \times E_{NG}) \tag{1}$$

where, $\$NG$ is the natural gas price, and E_{NG} is the natural gas consumption every 15 minutes.

However, (1) cannot show the energy saving process (i.e., the recovered hot water generation, distribution, and natural gas burning reduction), and therefore has no controllability on energy savings and natural gas burning minimization.

Therefore, the optimization equation should be changed from minimizing energy cost to maximizing energy utilization efficiency. Due to the long distance from the hot water generation side to the consumption end (i.e., heating coils or radiators), and the water flow speed limit in distribution pipes, the hot water distribution time cannot be neglected. In [9], the just-in-time (JIT) supply chain management method was first introduced into a district heating system. The JIT requires the desired amount of hot water to be dispatched to the desired consumption end at desired time [9]. This sub-section will introduce the hot water distribution optimization based on the idea of JIT aiming at increasing hot water utilization efficiency for space heating. In (2), it is shown to maximize the recovered heat utilization efficiency, which will result in less natural gas burned in the supplemental boiler, so the energy cost in heating zone is minimized.

$$\max \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{t=0}^{24\times 4} \frac{E_{jt}}{E_{i(t-t_{ijD})}} \tag{2}$$

where the indices are:

i = supplier = 1… n

j = consumer (radiator and/or reheat coil) = 1 … m

t = time period = 0 …t,

and the variables are:

E_{jt} = The amount of hot water received by consumer j during time period t (m^3)

$E_{i(t-t_{ijD})}$ = The amount of hot water sent by supplier i during time period $t-t_{ijD}$, which is the time that E_{jt} sent by supplier i (m^3),

and the parameters are:

D_{jt} = The predicted amount of hot water demanded in consumer j during time period t (m^3)

S_{ij} = The distance between supplier i and consumer j (m)

Q_{ijt} = The hot water flow rate in the distribution pipe from i to j during time interval t (m^3/s)

t_{ijD} = The distribution time of E_{jt} from supplier i to consumer j

$E^{\min}_{i(t-t_{ijD})}$ = The minimum hot water generation requirement during time interval $t-t_{ijD}$ in supplier i (m^3)

$E^{\max}_{i(t-t_{ijD})}$ = The maximum hot water generation during time period $t-t_{ijD}$ in supplier i (m^3),

subject to the constraints:

$$E_{i(t-t_{ijD})} > D_{jt} \tag{3}$$

$$D_{jt} \le E_{jt} < E^{\max}_{i(t-t_{ijD})} \tag{4}$$

$$E^{\min}_{i(t-t_{ijD})} \le E_{i(t-t_{ijD})} \le E^{\max}_{i(t-t_{ijD})} \tag{5}$$

B. Energy Mangement in the Heating Zone—The Decision Making Control of C-Agent

In a typical commercial central cooling system, the cold water from central chiller system is distributed to the cooling coils located at handlers, where the fans are keep blowing when cycled on, then the cooled air flow into the air-conditioned rooms with ventilation air. As the BCHP system was sized based on the heating load, the absorption chiller might not provide enough chilled water for space cooling because of limited recovered heat, so an electric chiller (i.e., water-compression chiller) must be included in the cooling energy zone. Similarly, the chilled water provided from BCHP system should be optimized for maximum usage. The electric chiller is cycled on when absorption chiller is not able to provide enough cooling for the demand. The objective function in (6) shows the optimization function embedded in the C-Agent, where the chilled water provided from electric chiller is also included, because the cooling demand is supposed to be satisfied by both absorption chiller and electric chiller.

In a central cooling system, where only one electric chiller is employed as cooling device, satisfies the commercial cooling demand. Therefore, only one absorption chiller and one electric chiller are employed here as cooling devices.

$$\max \sum_{q=1}^{k} \sum_{t=0}^{24\times 4} \frac{E_{qt}}{E^{a}_{(t-t_{aqD})} + E^{e}_{(t-t_{eqD})}} \tag{6}$$

where the indices are:

q = cooling coils = 1… k

t = time period = 1… t,

and the variables are:

E_{qt} = The amount of chilled water demanded in cooling coil

q during time period t (m^3)

$E^a_{(t-t_{aqD})}$ = The amount of chilled water sent by absorption chiller during time period $t-t_{aqD}$ (m^3)

$E^e_{(t-t_{eqD})}$ = The amount of chilled water sent by electric chiller during time period $t-t_{eqD}$ (m^3)

and the parameters are:

D_{qt} = The predicted amount of chilled water demanded in cooling coil q during time period t (m^3)

S_{cq} = The distance between central chillers and cooling coil q (m)

Q_{cqt} = The chilled water flow rate in the distribution pipes during time period t (m^3/s)

t_{cqD} = The distribution time of E_{qt} from central chillers to cooling coil q

$E^{\min}_{(t-t_{aqD})}$ = The minimum amount of chilled water can be provided from absorption chiller during time interval $t-t_{aqD}$ (m^3)

$E^{\max}_{(t-t_{aqD})}$ = The maximum amount of chilled can be provided from absorption chiller during time interval $t-t_{aqD}$ (m^3)

subject to the constraints:

$$E_{qt} \geq D_{qt} \tag{7}$$

$$0 \leq E^e_{(t-t_{eqD})} < D_{qt} \tag{8}$$

$$E^a_{(t-t_{aqD})} + E^e_{(t-t_{eqD})} > D_{qt} \tag{9}$$

$$E^{\min}_{(t-t_{aqD})} \leq E^a_{(t-t_{aqD})} \leq E^{\max}_{(t-t_{aqD})} \tag{10}$$

C. Energy Mangement in the Heating Zone—The Decision Making Control of E-Agent

The energy management in electrical zone has twofold objectives: (1) demand management, which is trying to reduce the peak electric load, and (2) communication with the utility for demand response information and real time prices of electricity and natural gas, trying to engage the building to participate in demand response, and uploading building's energy information on to the database for certain authorized entities to download and use in control actions.

In the building being considered in the CEBEMS, demand management is achieved by reducing the lighting power level and setting back the cooling setpoint during peak hours [10]. The demand management has three levels, from level 1 to level 3 as shown in Table I, where the demand management level is changing from moderate to more aggressive. The purpose of load management is to engage the building in demand response participation with the utility, so the building can make a profit towards net-zero cost building goal.

In the demand response of CEBEMS, the E-Agent continuously communicates with the utility for receiving energy prices and demand response information, and attempts to reduce local load demand to participate in demand response to make a profit. On the other hand, the building users' specific levels of comfort vis-à-vis thermostat setpoints and lighting levels are also respected. The local energy consumption and generation data will be collected by metering devices installed in the building, and then dispatched through a LAN to a database server (e.g., host server). The database server stores and archives the data and building users can access the database server and download appropriate real-time reports using dedicated or generic tools.

TABLE I.
THE DEMAND MANAGEMENT OF E-AGENT

Management Level	Lighting Power Level	Cooling Set Back
0	None	None
1	90%	0.5˚C
2	85%	1.0˚C
3	80%	1.5˚C

D. Interactions between E-, H- and C- agents

The interaction between the three agents is showed in Fig. 4. So far, the interaction is achieved by global shared information in the computer simulation software. However, in the future, the interaction between agents is planned to be implemented by possible candidate networking platforms.

IV. A Case Study to Achieve Minimum Energy Cost Energy Efficient Building

In this section, a case study is explored to show the energy saving capability of CEBEMS on a typical summer day and winter day based on the weather of Golden, CO. Then a test building [12] is simulated to examine the energy cost savings, where the utility energy price is based on synthetic data for rate provided by the EnergyPlus software. The following subsections describe some of the software applications used in this case study.

A. Building Energy Simulation Environment

1) EnergyPlus

EnergyPlus is a building energy analysis and simulation software, which is inherited from both BLAST and DOE-2 [10]. EnergyPlus can calculate the building heating and cooling loads, simulate building HVAC system and energy generation and consumption, etc. based on user's description of the building and its associated energy system [10]. The newer versions of EnergyPlus also include DG and RES (e.g. PV, fuel cell, wind turbine and micro-CHP system, etc) for energy efficient building applications.

2) AMPL

AMPL is a powerful modeling language for both linear and nonlinear optimization problems [11]. AMPL does not solve optimization problems directly, but it calls outside solver to solve problems, such as CPLEX, SNOPT, MINOS, IPOPT, KNITRO, LOQO, LANCELOT, the appropriate nonlinear programming (NLP) methods are SQP, Lagrange multipliers and IPM. AMPL is also a global solver; hence, there is no concern about reaching a local maxima or minima.

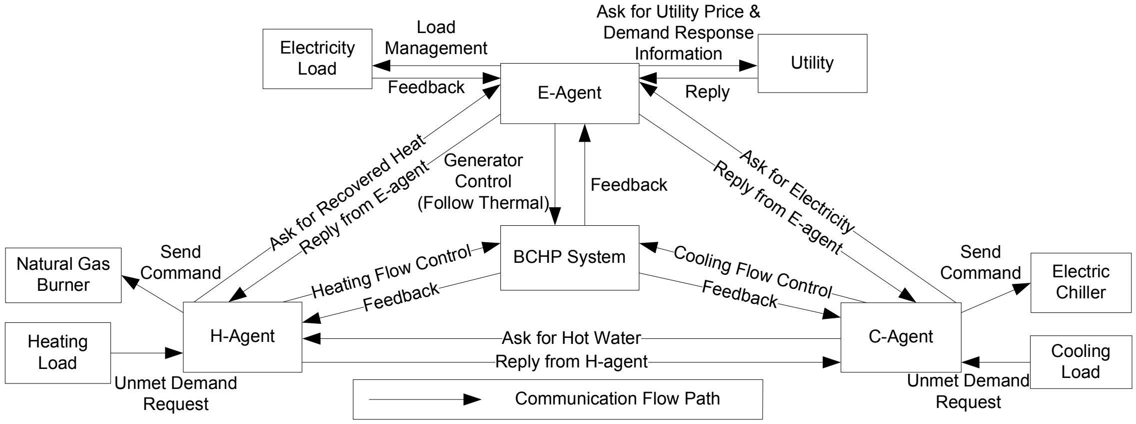

Fig. 4. The Interactions of CEBEMS

3) The Optimization Control from AMPL to the Building Model in EnergyPlus

In the heating zone and cooling zone, the space heating and cooling water flows are optimized (as introduced in Section III. A and B, respectively) by AMPL. The results will be the amount of water that should be sent from hot or chilled water suppliers during each time interval (15 minutes in this case). Then actuators embedded in the water pumps should change the water flow rate (i.e. Q_{ijt} and Q_{cqt} in heating and cooling zone, respectively) according to the optimized value calculated by H- and C- agents. EnergyPlus supports user-defined schedules of variable flow pumps. In this case, water demanded at the supply side in every 15 minutes interval is input into the schedule of appropriate pump as control signal from actuator, then the building heating and cooling loads are satisfied by the optimized water flow schedule calculated by AMPL.

B. Building Test System

For purposes of depicting the usefulness of this methodology, the CEBEMS is simulated for a smaller sized building, which is an example building provided in EnergyPlus. The building is a single-floor, rectangular, five-room setting of area 102.19 m^2. The detailed construction information of this building is available in EnergyPlus [12]. The building's energy and cost saving will be compared among: a) base case where the building is connected to the grid and air-conditioned by electric chiller and heated by heating coils with hot water from a natural gas boiler; b) BCHP model where the building has installed a micro-turbine combined with heat recovery for space heating and absorption chiller for space cooling. The natural gas burner and electric chiller are also installed as supplemental devices in BCHP; c) CEBEMS model, which is based on the BCHP model, and includes the E-, H- and C-Agents, as introduced in section III, in addition to the aspects of BCHP.

C. Results

Table II and III shows the energy consumption at the end uses compared with the base case, BCHP model and CEBEMS model. The energy consumers in the base case are HVAC system (i.e., cooling, boiler and fans as shown in Table II), interior and exterior lighting and interior equipment. The BCHP and CEBEMS model also have on-site generation with hot water loop, cold water loop, condensing loop and heat recovery loop and their associated water pumps installed as BCHP system, where the generator and pumps are energy consumers. The interior lighting, exterior lighting and interior equipment (i.e., appliances and miscellaneous loads) are base loads that are kept as constant unless load management from E-Agent is performed. The space heating and DHW needs are satisfied by boilers in the base case and by recovered heat in the other two models.

Analysis can be made from the three energy management system models compared in Tables II and III:

1) The comparison of base case and BCHP model shows the electricity usage in BCHP model has been significantly reduced (especially in the summer), but the natural gas consumption has been greatly increased due to the BCHP system installation that has changed the major energy consumption from electricity to natural gas.

TABLE II.
THE END USES OF BUILDING ENERGY CONSUMPTIONS COMPARED ON A TYPICAL SUMMER DAY IN GOLDEN, CO

Summer Day	Electricity (kWh)			Natural Gas (kWh)		
End Uses	Base Case	BCHP Model	CEBEMS Model	Base Case	BCHP Model	CEBEMS Model
Cooling	125.66	26.56	24.75	0	0	0
Interior Lighting	42.83	42.83	38.74	0	0	0
Exterior Lighting	0.62	0.62	0.62	0	0	0
Interior Equipment	23.78	23.78	23.78	137.37	137.37	137.37
Fans	30.83	30.83	30.83	0	0	0
Pumps	0	1.08	1.08	0	0	0
Water Systems	0	0	0	202.36	0	0
Generator	0	0	0	0	1546.29	1389.72
Total	253.4	125.7	119.8	339.74	1683.66	1527.09

TABLE III.
THE END USES OF BUILDING ENERGY CONSUMPTIONS COMPARED ON A TYPICAL WINTER DAY IN GOLDEN, CO

Winter Day	Electricity (kWh)			Natural Gas (kWh)		
End Uses	Base Case	BCHP Model	CEBEMS Model	Base Case	BCHP Model	CEBEMS Model
Cooling	18.54	18.54	16.95	0	0	0
Interior Lighting	42.83	42.83	39.21	0	0	0
Exterior Lighting	0.97	0.97	0.97	0	0	0
Interior Equipment	23.78	23.78	23.78	137.37	137.37	137.37
Fans	4.77	4.77	4.77	0	0	0
Pumps	0	1.14	1.14	0	0	0
Water Systems	0	0	0	271.25	0	0
Generator	0	0	0	0	2067.55	1962.45
Total	90.89	92.03	86.82	408.62	2204.92	2099.82

2) The comparison of BCHP model and CEBEMS model shows that both the electricity and natural gas consumption have been reduced in the CEBEMS model, because the H- and C- Agents have optimized the water generation and dispatch from on-site generator, so excessive hot water production is avoided.

3) The end energy uses shown in Tables II and III did not specify the energy sources, so on-site generation from the BCHP model and CEBEMS model still need to be investigated in Fig. 4 and 5.

In Fig. 4 and 5, only the electric and thermal demand of BCHP model are plotted here as comparative reference, because if no load management is performed by the E-Agent, the energy demand will be the same in these two models, if load management is performed, the energy demand in CEBEMS model will be less, so only the energy demand in the BCHP model need to be plotted as a comparative reference.

From the comparison shown in Figs. 4 and 5, the analysis is below:

1) In the BCHP model, both the thermal and electric generation is greater than the demand; the surplus electricity generation is sold back to the grid. Table II and III also shows the natural gas usage in boilers are zero in BCHP and CEBEMS model, so the heating demand is totally satisfied by recovered heat. Space cooling electricity usage in the BCHP model is greatly reduced compared with the base case, but the absorption chiller did not totally replace the electric chiller, because the BCHP system is sized based on the space heating demand, so the absorption chiller's chilled water output is limited by the hot water produced by the on-site generator.

2) In the CEBEMS model, the thermal energy output of BCHP system is optimized by H- and C-Agents, the thermal generation spikes are corrected with the calculated data, which is enough for the end uses and excessive hot water generation is avoided. Notice that the thermal generation in CEBEMS model can also be higher than the thermal generation of BCHP of BCHP model. This can be used as a preparation for the upcoming higher energy demand. As

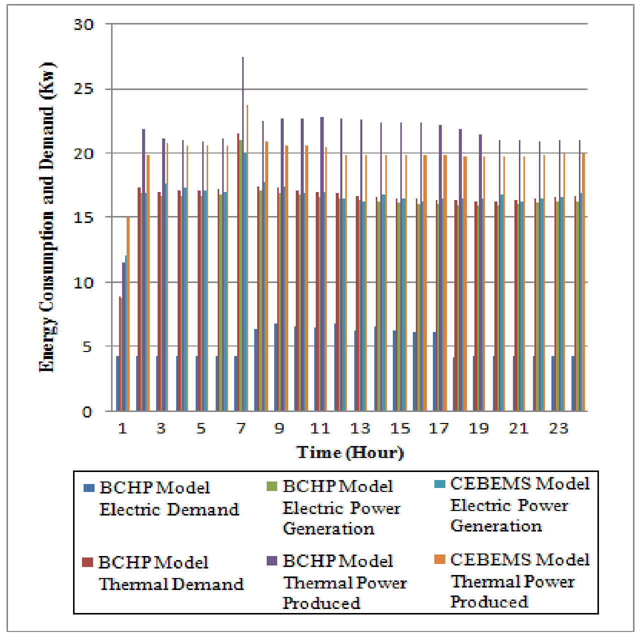

Fig. 4. The Energy Production of BCHP model and CEBEMS model on a typical summer day of Golden, Colorado

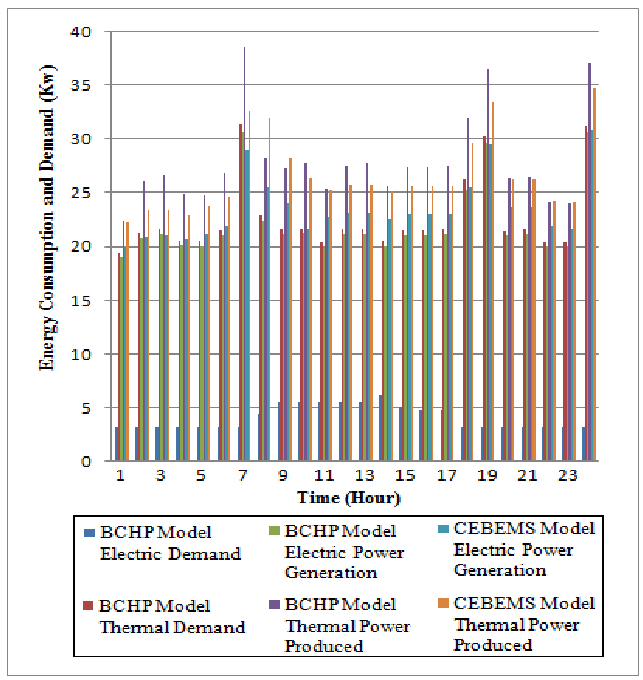

Fig. 5. The Energy Production of BCHP model and CEBEMS model on a typical winter day of Golden, Colorado

stated in Section III, the BCHP model is trying to follow the thermal load, but it is high in the early morning (i.e. 7AM in this case) and evening (i.e. 7PM in this case), so the associated electric generation from the on-site generation should also go up and down quickly, which will potentially decrease the energy efficiency of the generator. In the CEBEMS model the thermal output from the generator is relatively smoother than that in the BCHP model, so the

TABLE IV.
THE ENERGY COST COMPARED ON A TYPICAL WINTER DAY AND SUMMER DAY

	Typical Summer Day			Typical Winter Day		
Cost ($)	Base Case	BCHP Model	CEBEMS Model	Base Case	BCHP Model	CEBEM Model
Energy Charges	25.92	12.45	11.39	12.33	9.42	8.57
Demand Charges	174.58	33.94	28.34	33.13	12.35	10.56
Service Charges	2.91	2.91	0.425	2.91	2.91	0.425
Subtotal	203.41	49.3	40.15	48.37	24.68	19.56
Taxes	16.27	3.94	3.21	3.87	1.9744	1.56
Total	219.68	53.24	43.37	52.24	26.65	21.12

associated electric output is also smoother, which helps the generator to avoid some quick responding to the sudden rising demand.

Table IV Shows the energy cost of the base case, BCHP model and CEBEMS model based on the utility dynamic energy price provided as synthetic data in the example model in EnergyPlus [12]. The total utility cost shown in Table IV is calculated by the following method: the sum of energy charges, demand charges and service charges constitutes the basis, which is then added with adjustments and surcharges that constitute the subtotal, added with the taxes (i.e., 8% in this case). In this case, the adjustments and surcharges are zero, so they are not shown here in Table IV. For the energy charges, unit cost of electricity and natural gas price are defined as 10.23cents/kWh and $ 9.55/MCF, respectively.
The service charges are determined by the electricity demand of the building from the utility. If the building's peak hour electrical demand is above 10 kW, then the service charge will be $87.3 per month; if not, then the service charge will be $12.74 per month. The services charges applied here are divided by 30 to reflect the cost for one day of the month. The demand charges are employing block rates determined by building service charges type. For the detailed block rates, please refer [12]. In this case study, the energy cost of the BCHP model has a significant cost savings compared with the base case, because the BCHP system is energy efficient in nature; the CEBEMS model has more energy cost savings compared with the BCHP model, because cyber enabled MAS decision-making control systems work toward optimizing the energy utilization. However, the real cost saving amount will be changed if a different utility tariff is used in the simulation.

V. CONCLUSIONS

This paper investigated an application of MAS for cyber enabled energy management of building structures known as CEBEMS. The efficient building energy management system is expected to be achieved through both physical and cyber aspects of the building, such that the BCHP building model provides an applicable building physical aspect for energy efficient buildings, while the CEBEMS model adds the cyber aspect on the BCHP model, which optimizes the energy generation and distribution. However, the test building chosen in the example shown in this paper is a typical food service center, whose thermal demand is relatively constant compared with common commercial office building. In the future, the CEBEMS will be applied into an office building to investigate the energy and cost savings.

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VII. REFERENCES

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