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Research Article

OPTIMAL ENERGY MANAGEMENT FOR RESIDENTIAL MICROGRID WITH THERMAL AND ELECTRICAL LOADS

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ABSTRACT
With developing microgrid in residential districts, significant energy consumption can be saved through optimal scheduling of household appliances, production and storage components. In this paper a novel energy management strategy is proposed for residential microgrid (RMG) to coordinate its thermal and electrical loads. To achieve this, an optimization problem is formulated and solved with objective function of minimizing total energy cost taking into account comfortable lifestyle in terms of desired hot water and indoor temperature. The simulation results demonstrate that the proposed model not only reduces total energy cost, but also ensures a convenient lifestyle for the consumer.

Keywords*: Residential Microgrids, Thermal and Electrical Load, Energy Management Strategy, Linear Programming Optimization*

INTRODUCTION

Rapid rise in fossil fuel price along with environmental concerns are major incentives for implementing energy systems (i.e., microgrids) with higher efficiency in distribution level. The microgrid can be regarded as a controllable entity of loads and micro-sources which provides electrical and thermal needs of its residential district (e.g., household or commercial building) (Tsikalakis and Hatziargyriou, 2011). Due to main technological advantages of microgrid, integrating of energy production, conversion and storage units such as renewable energy resources, micro combine heat and power (µ-CHP), battery and thermal energy storage has become enabled (Derakhshandeh *et al.*, 2013).

The µ-CHP unit is an energy conversion system with maximum electric capacity equal to 15 kW that produces both electrical and heat energy at the same time; Consequently, total residential microgrid efficacy is made better by utilizing loosed heat to satisfy thermal loads (Paepe *et al.*, 2006). However, the main issue in optimal energy management of residential microgrid is to coordinate thermal and electrical loads. Several studies have been proposed on optimal energy management of microgrids. Nguyen *et al.*, (2014) study the energy scheduling for a household equipped with a solar assisted heating, ventilation, and air conditioning, and water heating system in the real-time pricing environment with objective of minimizing the electricity cost while maintaining user's thermal comfort requirements. Anvari-moghaddam *et al.*, (2015) propose a multi-objective optimization framework for optimal energy management of residential buildings. The proposed algorithm could not only reduce the domestic energy usage and utility bills, but also ensure an optimal task scheduling and a thermal comfort zone for the inhabitants. Igualada *et al.*, (2014) present an optimization model to manage a residential microgrid including a charging spot with a vehicle-to-grid system and renewable energy sources. The model is executed one-day-ahead and generates a schedule for all components of the microgrid. Yao *et al.*, (2014) presents a control scheme for thermal management in smart buildings based on predictive power admission control. This approach combines model predictive control with budget schedulability analysis in order to reduce peak power consumption as well as ensure thermal comfort. The obtain results demonstrate that effective peak power demand is reduced by means of the optimal scheduling and cooperative operation of multiple thermal appliances. Ahmadi *et al.*, (2015) develop an analytical model for a residential microgrid under a collaborative environment. For this purpose, consumers assign priority to their appliances. Then, the microgrid informs consumers about their real-time consumption and economic benefits associated with their participation in collaborative consumption. Accordingly, consumers can evaluate suggested alternatives prior to using appliances and consequentially make better decisions.

The available infrastructures in microgrids in terms of control and communication, allow to accomplishing demand response (DR) programs. Pourmousavi *et al.*, (2015) propose a multi-timescale cost-effective power management algorithm for islanded MG operation targeting generation, storage, and demand management. Jiang and Fei (2014) propos an energy ecosystem; a cost-effective smart microgrid based on intelligent hierarchical agents with dynamic demand response and distributed energy resource management.

In this regard, this paper aims at resenting an optimal energy management for residential microgrids in order to well coordinate electrical and thermal loads. For this purpose, an optimization problem is formulated and solved with objective function of minimizing total energy cost taking into account comfortable lifestyle in terms of desired hot water and indoor temperature. Basically, the novelty of this work is highlighted as following:

- A comprehensive energy management model for residential microgrids to coordinate electrical and thermal loads.
- Implementing demand response programs including shiftable and non-shiftable loads and µ-CHP unit.

The reminder of this paper is organized as follow. In section Thermal loads model, the temperature dependent model of thermal loads is presented. In section problem formulation, the objective function and constraints of optimization problem are presented. The simulation results are presented in section simulation results. Finally, the conclusions are discussed in section conclusion.

Thermal Loads Model

Thermal loads of residential microgrid are modeled by using hot water temperature and air temperature. To model the heat tank storage, as shown in figure 1, the energy equivalent of hot water at every hour of scheduling is assumed and water flow dynamic is ignored.

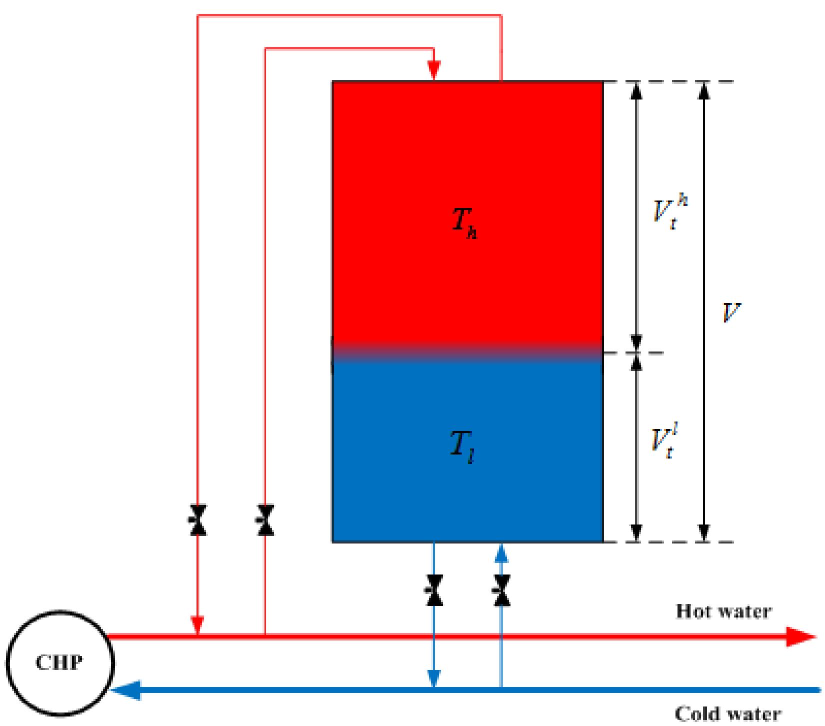

Figure 1: Heat tank storage

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The energy equivalent of hot water is changed when cold water entered or μ-CHP generates heat. Therefore, the hot water temperature at every hour of scheduling can be express by the following equation (Chen *et al.*, 2014):

$$T_d(t+1) = \frac{V_l(t)\times(T_l(t)-T_d(t))+V\times T_d(t)}{V} + \frac{Q_{CHP}(t)-Q_{indoor}(t)}{V\times C_{water}} \quad (1)$$

Where, V_l and V are the volume of cold water and total volume of heat tank, respectively. Meanwhile, T_l and T_d are temperature of cold water and desired temperature of supply pipe to residential districts. The μ-CHP generated heat is denoted by Q_{CHP} while the required heat for setting the building temperature is denoted by Q_{indoor} at each hour. C_{water} is specific heat of water.

According to the building temperature model, as shown in figure 2, the air temperature at every hour of scheduling can be express by the following equation (Scott *et al.*, 2013):

$$T_{indoor}(t+1) = T_{indoor}(t)\times \exp\left(\frac{-1}{\tau}\right) + \left(R\times Q_{indoor}(t) + T_{outdoor}(t)\right)\times\left(1-\exp\left(\frac{-1}{\tau}\right)\right) \quad (2)$$

Where, T_{indoor} and $T_{outdoor}$ are desired indoor temperature and outdoor temperate, respectively. Thermal resistance of building wall is denoted by R and thermal time constant denoted by $\tau = R\times C_{air}$. Specific heat of air is denoted by C_{air}.

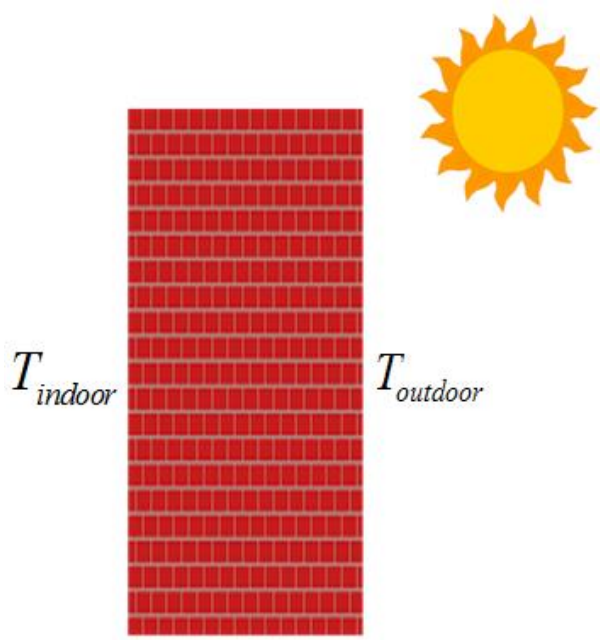

Figure 2: The building temperature model

Problem Formulation

Before representing the problem formulation, the control process of μ-CHP is explained in this section. Because of higher efficiency for thermal generation of μ-CHP rather than electrical generation, the control process is design to meet thermal loads of residential microgrid with high priority while electrical generation is proportion of thermal generation with constant ratio.

The control process of μ-CHP is illustrated in figure 3 in which only the thermal loads at every hour of scheduling are satisfied without taking into account the electrical loads. The temperature dependent modeling of thermal allow deviating hot water temperature and indoor temperature around acceptable interval of desired temperature considering customers comfortable lifestyle. This issue will explain in detail in the following of this section.

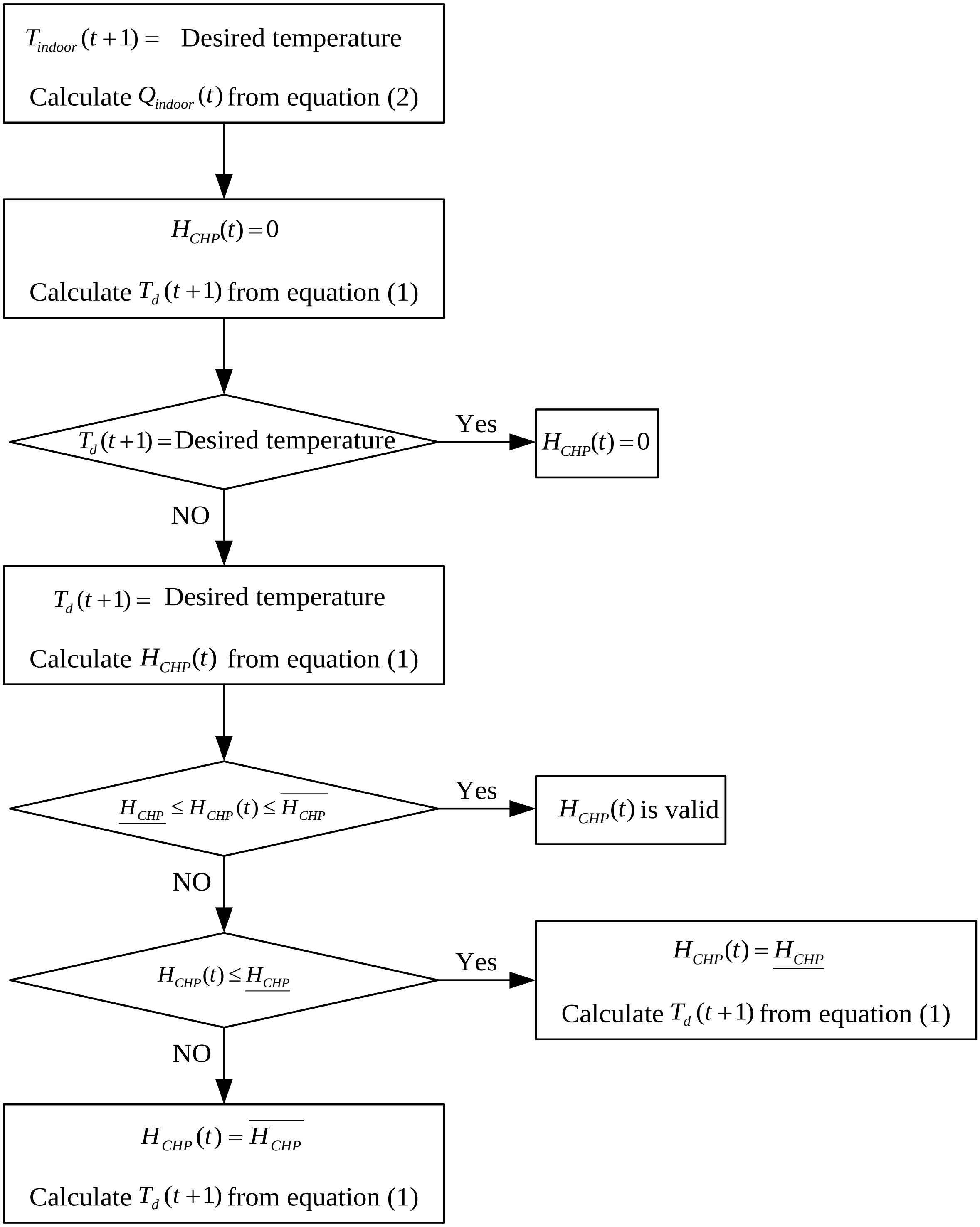

Figure 3: Control process of µ-CHP

Objective Function

The objective function of energy management is to minimize total cost of electrical power imported from the network and natural gas consumption of µ-CHP over the scheduling horizon:

$$OF = \sum_{t=1}^{24}\{P_{grid}(t) \times \pi_{TOU}(t) + F_{CHP}(t) \times \pi_{NG}\} \tag{3}$$

Where, P_{grid} and F_{CHP} are electrical power imported from network and natural gas consumption of µ-CHP, respectively. It is assumed that electricity price, π_{TOU}, to be same in every hour of scheduling and natural gas price, π_{NG} to be same for all hours of scheduling.

Constraints

Supply demand balance: The sum of the imported power from network, power generation from µ-CHP and battery energy storage must be equal to demand. Supply demand balance constraint without and with considering DR programs can be express by the following equations, respectively:

$$P_{grid}(t) - P_b(t) + P_{CHP}(t) = P_L(t) \tag{4}$$

$$P_{grid}(t) - P_b(t) + P_{CHP}(t) = P_{Lnsh}(t) + \sum_{n=1}^{N} P_{Lsh}(n,t) \tag{5}$$

Where, P_b and P_L are battery net output power and electrical load of residential microgrid. Meanwhile, P_{Lnsh} and P_{Lsh} are non-shiftable and shiftable electrical load of residential microgrid.

Costumer's Comfortable Lifestyle: The following equations express customer's comfortable lifestyle in terms of desired hot water and indoor temperature:

$$\underline{T_d} \leq T_d(t) \leq \overline{T_d} \tag{6}$$

$$\underline{T_{indoor}} \leq T_{indoor}(t) \leq \overline{T_{indoor}} \tag{7}$$

Where, $\underline{T_d}$ and $\overline{T_d}$ are minimum and maximum desired temperature of supply pipe to residential districts, respectively. Meanwhile, $\underline{T_{indoor}}$ and $\overline{T_{indoor}}$ are minimum and maximum desired indoor temperature, respectively.

µ-CHP model: The power and heat energy generated by µ-CHP should adhere to output constraints as well as ramp rate constraints:

$$u_{CHP}(t) \times \underline{P_{CHP}} \leq P_{CHP}(t) \leq u_{CHP}(t) \times \overline{P_{CHP}} \tag{8}$$

$$u_{CHP}(t) \times \underline{H_{CHP}} \leq H_{CHP}(t) \leq u_{CHP}(t) \times \overline{H_{CHP}} \tag{9}$$

$$|P_{CHP}(t) - P_{CHP}(t-1)| \leq RR \tag{10}$$

$$|H_{CHP}(t) - H_{CHP}(t-1)| \leq \frac{\eta_{th}}{\eta_e} \times RR \tag{11}$$

Where, a binary variable, u_{CHP}, is corresponding to µ-CHP commitment and ramp rate of µ-CHP unit is RR. Meanwhile, the µ-CHP electrical and thermal efficiency is denoted by η_e and η_{th}, respectively. As mention before, electrical generation of µ-CHP unit is proportion of thermal generation with constant ratio:

$$P_{CHP}(t) = \frac{\eta_{th}}{\eta_e} \times H_{CHP}(t) \tag{12}$$

Battery energy storage model: The battery energy storage unit can be charged in off-peak hours with low prices and sell the storage energy to the microgrid during peak hours. The following equations express the battery energy storage unit:

$$0 \leq \frac{P_b^{ch}(t)}{\eta_{ch}} \leq u_{ch}(t) \times \overline{P_{ch}} \tag{13}$$

$$0 \leq P_b^{dch}(t) \times \eta_{dch} \leq u_{dch}(t) \times \overline{P_{dch}} \tag{14}$$

$$u_{ch}(t) + u_{dch}(t) \leq 1 \tag{15}$$

$$P_b(t) = \frac{P_b^{ch}(t)}{\eta_{ch}} - P_b^{dch}(t) \times \eta_{dch} \tag{16}$$

$$SOC(t+1) = SOC(t) + \frac{P_b^{ch}(t) - P_b^{dch}(t)}{E_b} \tag{17}$$

$$\underline{SOC} \leq SOC(t) \leq \overline{SOC} \tag{18}$$

Where, P_b^{ch} and P_b^{dch} are charging power and discharging power of battery energy storage unit, respectively. The charging and discharging efficiency are denoted by η_{ch} and η_{dch}, respectively. Meanwhile charging and discharging status are denoted by u_{ch} and u_{dch}, respectively. The battery state of charge with capacity equal to E_b is denoted by SOC.

Demand response model: Having price tariffs together with exact electrical load profile furnished by the smart meter, customers can practically take part in demand response programs. In this study customer can take part in DR programs using shiftable appliance. This appliance can be easily scheduled based on price tariffs without defecting important discomfort for customers. The scheduled constraints for shiftable appliance n can be expressed as follows:

$$P_{Lsh}(n,t) = \frac{E_n}{MRT_n} \quad (19)$$

$$\sum_{n=1}^{N} u_{Lsh}(n,t) = E_n \quad (20)$$

Where, E_n is energy consumption of customer n and MRT_n is minimum require time to finish task for customer n.

RESULTS AND DISCUSSION

Simulation Results

The proposed model is applied to a residential building over a daily time horizon with hourly time interval. The electrical demand of residential building and the allotment of every appliance which are measured by means of installed smart meter are illustrated in figure 4. Meanwhile, the hot water demand of building is depicted in figure 5. A μ-CHP unit with electrical output of 3 kW and a battery energy storage with the capacity of 6.86 kWh are considered. Meanwhile, the volume of heat thank is assumed to be 150 litter.

In this paper, five shiftable loads are considered which their operational parameters are given in table 1. Other technical parameters of system components as well as time of use (TOU) price tariffs are shown in table 2 and 3, respectively. Meanwhile, the price of natural gas is assumed to be constant and equal to 0.182 $^{\$}/_{m^3}$. The proposed model is implemented in GAMS software and solved by CPLEX solver on a Pentium V, 2.6 GHz CPU with 4 GB of RAM.

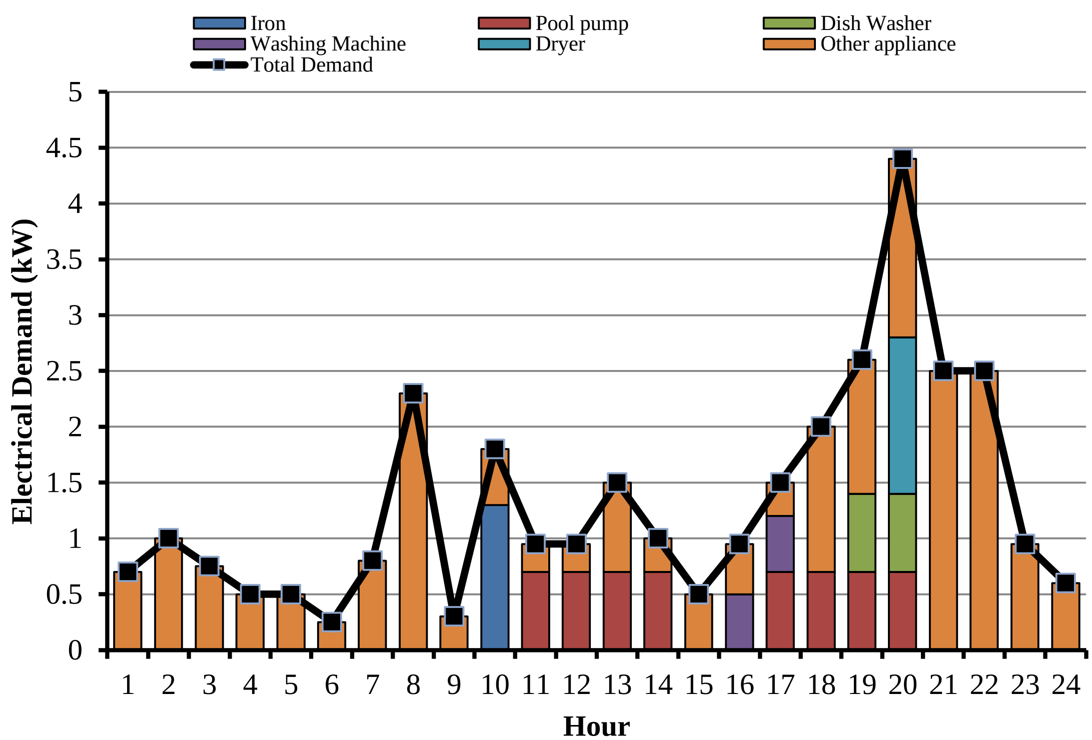

Figure 4: Electrical demand of residential microgrid

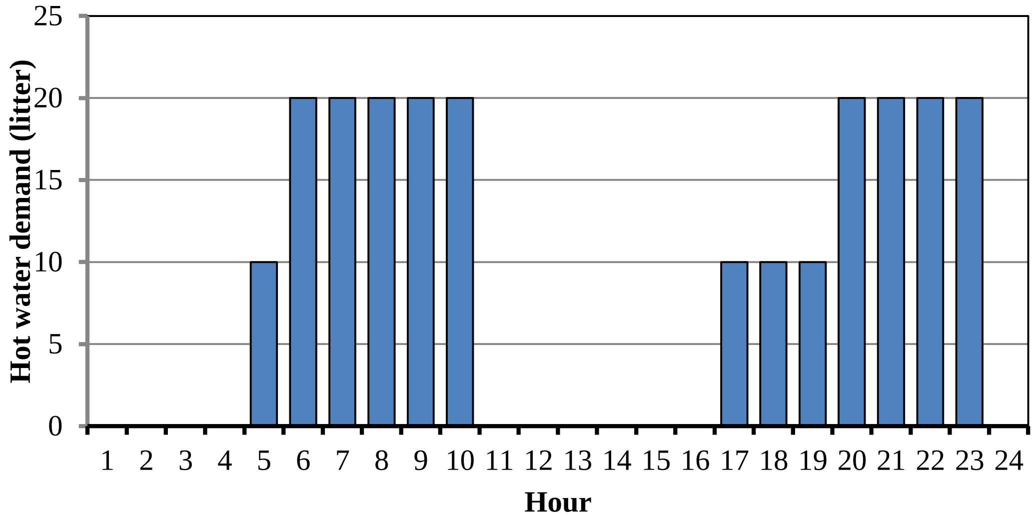

Figure 5: Hot water demand of residential microgrid

Table 1: Operational parameters of shiftable loads

Shiftable load	$E\ (kWh)$	$MRT\ (h)$
Iron	1.3	1
Pool pump	1.1	2
Dish washer	2.7	2
Washing machine	1	2
Dryer	1.3	1

Table 2: Technical parameters of system components

Parameter	**Value**	**Unit**
R	18	$C/_{kW}$
Indoor desired temperature	25	C
$\underline{T_{indoor}}, \overline{T_{indoor}}$	23, 27	C
Hot water desired temperature	70	C
$\underline{T_d}, \overline{T_d}$	60, 80	C
C_{air}	0.525	$kWh/_{C}$
C_{water}	0.01164	$kWh/_{C}$
V	150	Litter
$\underline{P_{CHP}}, \overline{P_{CHP}}$	0.3, 3	kW
$\underline{H_{CHP}}, \overline{H_{CHP}}$	0.5, 5	kW
RR	2.5	$kW/_{h}$
η_{th}, η_e	30, 50	%
$\overline{P_{ch}}, \overline{P_{dch}}$	1.4	kW
$\underline{SOC}, \overline{SOC}$	0.3, 1	Per unit
η_{ch}, η_{dch}	0.85, 0.98	%

Table 3: Time of use (TOU) price tariffs

Hour	**Price** ($^{\$}/_{kWh}$)	**Hour**	**Price** ($^{\$}/_{kWh}$)
1	0.062	13	0.092
2	0.062	14	0.092
3	0.062	15	0.092
4	0.062	16	0.092
5	0.062	17	0.092
6	0.062	18	0.108
7	0.062	19	0.108
8	0.108	20	0.062
9	0.108	21	0.062
10	0.108	22	0.062
11	0.108	23	0.062
12	0.092	24	0.062

In order to evaluate the effeteness of proposed model, two case studies are addressed as follows:
Case 1: In the first case study no DR program is considered.
Case 2: In the second case study the smart grid infrastructures are assumed to be inhabited and therefore DR program can be implemented.
The electrical generation of μ-CHP as well as the electrical demand in case 1 and 2 are shown in figure 6 and 7, respectively.

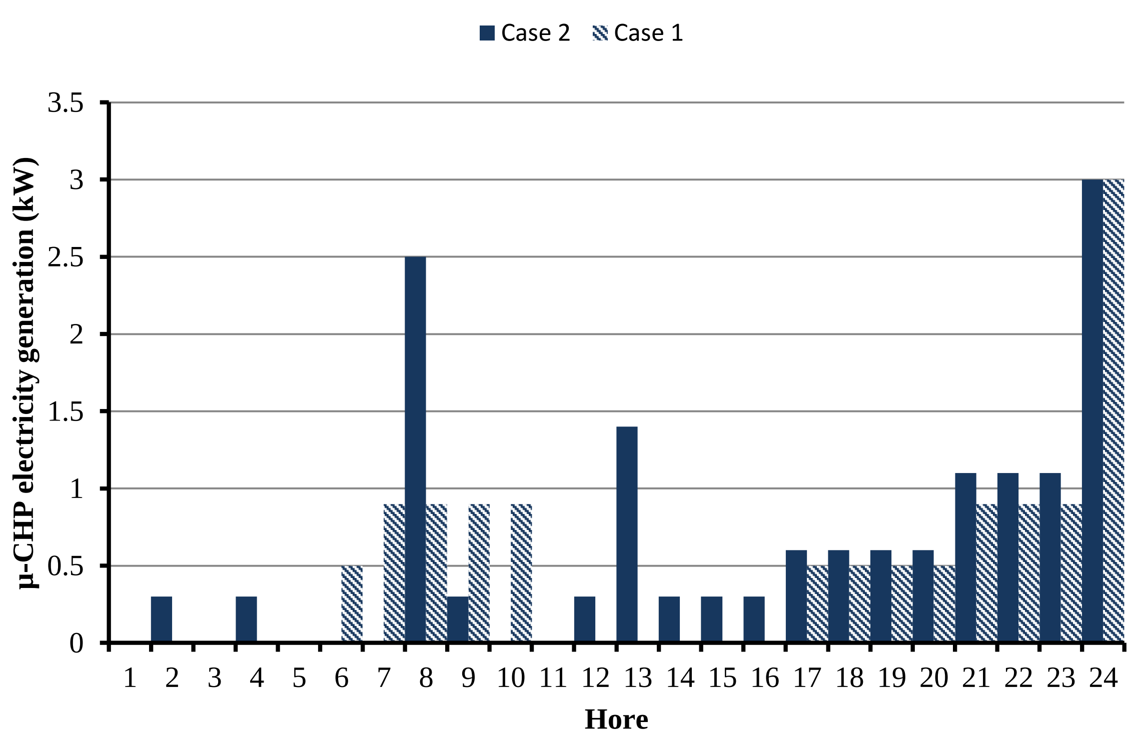

Figure 6: Electrical generation of μ-CHP in case 1 and 2

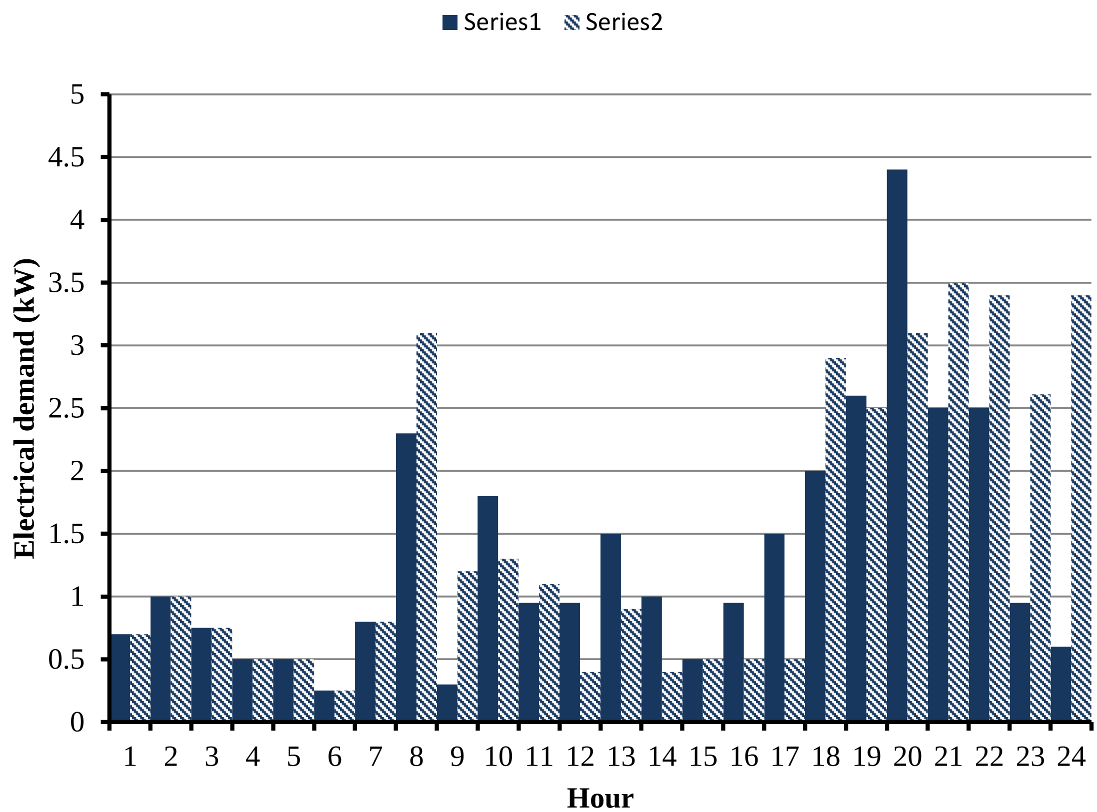

Figure 7: Electrical demand in case 1 and 2

As shown in figure 6, in case 1 the µ-CHP electricity generation, which indicates the thermal generation with a constant ratio, mostly follows the thermal demand as directed in figure 5 to preserve hot water and air temperature at a fix level. In case 2, with considering demand response programs, µ-CHP can generate more electricity specifically in the hours with high prices which leads to operation cost reduction of residential microgrid.

As shown in figure 7, the electrical demand of residential microgrid is modified in such a way that yields in more smother load profile by shaving the peak load and rescheduling the shiftable load to operate in hours with low prices, e.g., last night.

The operation cost of residential microgrid in case 1 and 2 are compared in table 4. As it can be seen, by implementing demand response programs, the operation cost of residential microgrid is reduced significantly.

Table 4: Microgrid operation cost

Case study	**Operation cost of microgrid** ($)
Case 1	140.982
Case 2	60.962

The indoor, outdoor and water temperatures in case 2 are shown in figure 8. As shown, the indoor and water temperature try to follow desired prescribed set point in the every hour of scheduling. However, In the hours with high prices and peak load, wider temperature devotion can be seen which leads to operation cost reduction of residential microgrid.

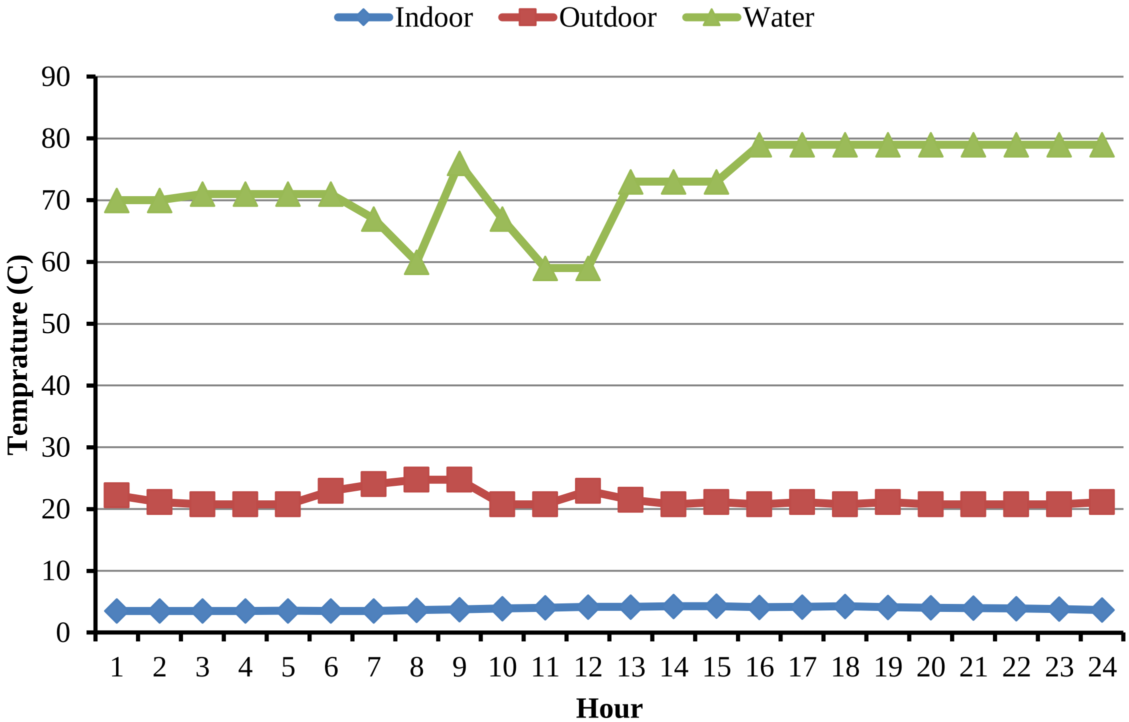

Figure 8: Indoor, outdoor and water temperatures in case 2

Conclusion

In this paper, an optimal thermal and electrical energy management has been developed for a typical residential microgrid. An optimization problem has been formulated and solved with objective function of minimizing total energy cost while considering customers comfortable lifestyle in terms of desired hot water and indoor temperature. Simulation results demonstrate that coordination of thermal loads with electrical load lead to cost reduction of residential microgrid. In other word, it enables more flexibility and facilitates more µ-CHP electricity generation which leads to cost saving.

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