An Optimal Dispatch Algorithm for Managing Residential Distributed Energy Resources

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***Abstract*—This paper deals with a residential hybrid thermal/electrical grid-connected home energy system, including a fuel-cell with combined heat and power (CHP) and a battery as energy storage system (ESS). A day-ahead scheduling algorithm for managing different resources is developed to generate an efficient look-up table that determines an optimal operation schedule for the distributed energy resources at each time interval, so that the operation cost of a smart house is minimized. The impact of the electricity tariff and the efficiency of the energy storage system are considered when optimizing the operation schedules.**

***Index Terms*—Battery efficiency, combined heat and power (CHP) system, electricity tariff, scheduling optimization, smart home.**

NOMENCLATURE

α_1	Fuel cell startup cost.
α_2	Fuel cell shut down cost.
$P_{FC,\max}$	Maximum limit of fuel cell generated power.
$P_{FC,\min}$	Minimum limit of fuel cell generated power.
$\Delta P_{FC,U}$	Upper limit of ramp rate of fuel cell.
$\Delta P_{FC,D}$	Lower limit of ramp rate of fuel cell.
T	Length of time interval.
W_{init}	Initial energy available in battery.
W	Available energy in battery.
η_{ch}	Efficiency of battery charging.
η_{dch}	Efficiency of battery discharging.
$W_{\max}$	Maximum energy limit of battery.
$W_{\min}$	Minimum energy limit of battery.
$P_{Bch\max}$	Maximum limit of battery charging rate.
$P_{Bdch\max}$	Maximum limit of battery discharging rate.
C_{U_b}	Maximum value of utility purchasing electricity cost per kW.
C_{gas_b}	Cost of purchasing natural gas per kW.
C_{FC}	Total cost of fuel cell.
C_U	Total cost of utility.
C_B	Total cost of battery.
C_{gas}	Total cost of purchasing gas.
P_{hFC}	Heat power produced by fuel cell.
P_{eFC}	Electrical power produced by fuel cell.
η_{FC}	Efficiency of fuel cell.
P_{gas}	Heat power produced directly from gas.
MU	Normalized price of electricity tariff.
P_U	Purchased power from utility by home.
C_{B_b}	Operation and maintenance cost of battery per kW.
P_B	Output power of battery.
P_{eL}	Electrical load demand.
P_{hL}	Thermal load power.
PLR	Part Load Ratio.
r_{FC}	Electrical to thermal power ratio of fuel cell.
i	Number of interval that appears as variables subscript and indicates value of that variable in i-th interval.

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I. INTRODUCTION

ELECTRICAL and thermal demands in a home energy system can be provided by cogeneration systems. The Combined Heat and Power (CHP) system is a major part of the integrated energy system. A large number of studies around the world have been devoted to studying its application in energy systems [1]–[6].

CHP has been technologically promoted in recent years. Another side is the problem of establishing experimental blocks, which has been facilitated by setting up appropriate policies [7]–[9].

The use of CHP systems for residential loads will be increased if economic operation of the integrated energy system is studied well. Economic operation of a fuel cell (FC)-based CHP system has been studied in [9], [10], in which results of four cases with different recovery heat dispatching have been compared. A combined cooling, heating and power (CCHP) system including a gas turbine and batteries has been investigated in [11]. Its results show that the CCHP system with storage device has great advantages. It has also been demonstrated that efficiency of the system decreases gradually with load reduction; however, the system operation cost has not been considered.

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The integrated energy system including diesel generator, wind turbine, photovoltaic (PV) array, micro-turbine, FC, and a battery as a storage device has been studied in [12]. In this system, the operating cost has been optimized considering emission reduction of NOx, SO_2 and CO_2.

The energy system including wind energy, PV, heat recovery boiler and battery has been investigated in [7]. The system operation cost is calculated and effects of the battery usage and electricity tariff on the energy dispatching cost are studied. However, optimal scheduling of different energy resources has not been considered and the minimum value of daily operation cost of the integrated energy system has not been determined.

A CHP system composed of a proton exchange membrane fuel cell (PEMFC) and a wind turbine has been established in [9]. Investigating the economic operation of this integrated power plant using the evolutionary algorithm, [9] leads to four different methods for dealing with the recovered heat.

An optimization model considering a CHP system has been proposed in [13], which includes several distributed energy resources. The minimum operation cost of this system has been determined by optimizing the model.

The CHP system operation with a storage device installed in a house is studied in this paper from an economic point of view. The under study integrated energy system consists of FC, battery, thermal, and electrical loads. The system is supplied by a natural gas resource and electrical grid. All the mentioned devices are economically modeled and the one-day ahead operating cost of the home energy system is minimized using the Colonial Competitive Algorithm (CCA). The effects of the battery efficiency and electricity tariff are also considered in this paper. It is shown that efficiency of the battery has a major effect on the system operating cost. Higher efficiency leads to lower cost in the home energy system. In addition, minimum value of the battery efficiency is found such that it cooperates in the system energy routing. Moreover, effectiveness of the battery usage and role of the cooperation of the battery in the energy system are discussed in the paper. Results of the cost minimization process determine scheduling of different energy resources gathered in a look-up table. Generations of different energy resources can be determined according to this table in each time interval. Using this table guarantees that the electrical/thermal demands are met at minimum operation cost.

This integrated energy system has been modeled in [6] and its operation cost has been minimized using the Harmony Search Algorithm (HSA). In [6], efficiencies of battery charging and discharging procedures have not been considered. In this paper, the economic model of the integrated energy system is investigated more accurately. Moreover, global minimum of the system cost function is found using CCA. The results of optimization of the system operating cost using HSA and CCA are compared and better performance of the proposed approach than [6] is demonstrated.

This paper is organized as follows: In the next section, the smart home energy system and energy management strategies are introduced. The problem of energy system is formulated and the model constraints are also described in Section II. In Section III, CCA is described as an optimization tool. Finally, in Section IV, the simulation results are presented and discussed.

II. Home Energy System and Optimization Model

The proposed home energy system consists of a battery, a FC and thermal and electrical loads, as illustrated in Fig. 1. The thermal load can be supplied by either natural gas resources or recovered heat from the FC. The electrical load can be supplied by the main grid, FC, or the battery.

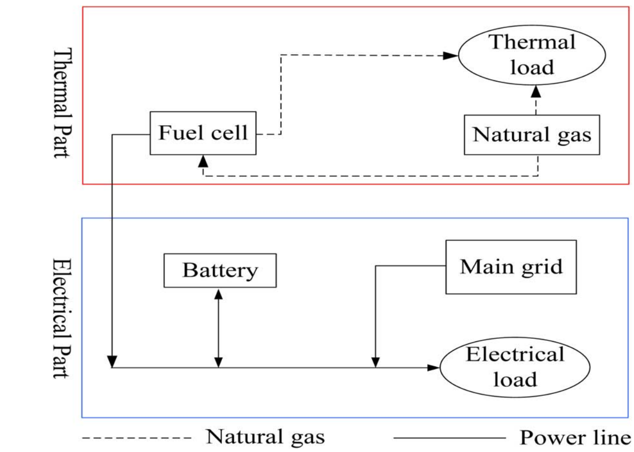

Fig. 1. Integrated home energy system.

The main role of the energy management system is to minimize the operating cost for supplying demand of an individual house. In order to effectively use available energy resources, operation scheduling should be worked out one day or longer in advance. It is assumed that the predicted values of heat and electricity demands are available one day ahead in the optimization model studied in this paper.

It should be noted that the goal of this study is to minimize the operating costs. Therefore, it is assumed that the home energy system components are previously installed and there is no need to consider installation costs.

A. Objective Function

The following objective function should be minimized:

$$\min\left(\sum_i C_{U,i} + \sum_i C_{FC,i} + \sum_i C_{gas,i} + \sum_i C_{B,i}\right) \quad (1)$$

where:

$$C_{U,i} = MU_i C_{U_b} P_{U,i} T \quad (2)$$

$$C_{FC,i} = \begin{cases} C_{gas_b} T\left(\frac{P_{eFC,i}}{\eta_{FC,i}}\right) + \alpha_1 & if\ P_{eFC,i} > 0, \\ & \quad P_{eFC,i-1} = 0 \\ \alpha_2 & if\ P_{eFC,i-1} > 0, \\ & \quad P_{eFC,i} = 0 \\ C_{gas_b} T\left(\frac{P_{eFC,i}}{\eta_{FC,i}}\right) & else \end{cases} \quad (3)$$

$$C_{gas,i} = C_{gas_b} P_{gas,i} T \quad (4)$$

$$C_{Bi} = \begin{cases} C_{B_b} P_{B,i}\, T & if\ P_{B,i} \geq 0 \\ -C_{B_b} P_{B,i}\, T & if\ P_{B,i} < 0 \end{cases} \quad (5)$$

It should be noted that $P_{B,i}$ is negative in charging mode and positive in discharging mode. In order to have a positive battery operating cost in its different operation modes, $C_{B,i}$ is calculated based on (5). Finally, MU used in (2), will be defined later in Section II-D.

B. Constraints of Power Balance

If no load is allowed to be curtailed, the model should meet electrical and thermal demands completely. For the electrical power balance, if the load curtailment is avoided, then:

$$P_{eFC,i} + P_{B,i} + P_{U,i} - P_{eL,i} = 0 \quad (6)$$

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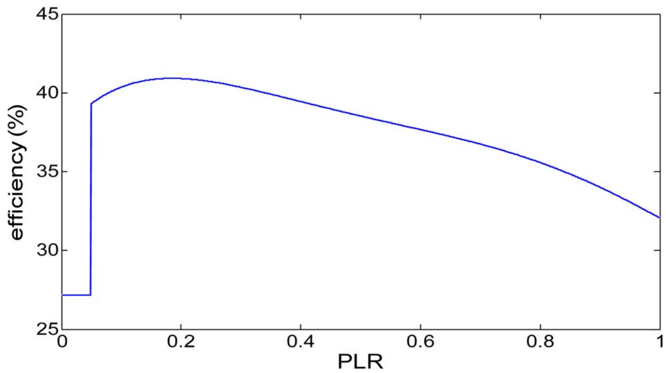

Fig. 2. Efficiency to PLR in FC.

where $P_{B,i}$ is negative or positive in charging and discharging modes of the battery operation, respectively.

Similarly, in the case that no heat storage device is installed, the following equation indicates the thermal power balance:

$$P_{gas,i} + P_{hFC,i} - P_{hL,i} = 0 \tag{7}$$

C. Constraints of Devices

Available energy in a battery is limited to its capacity. In other words, state of charge of a battery cannot violate the specified margins, as stated in the following inequality:

$$W_{\min} < W_i < W_{\max} \tag{8}$$

Ideally, if the battery is discharged (charged) with, its energy is reduced (increased) by $P_{B,i}\Delta t$ while in a real condition, the energy reduction of a battery, which is discharged with the rate of $P_{B,i}$ is equal to $((P_{B,i}\Delta t)/\eta_{dch})$ and can be simplified for $\Delta t = 1$ h as follows:

$$W_i = W_{i-1} - \left(\frac{P_{B,i}}{\eta_{dch}}\right) \tag{9}$$

A battery is charged by the energy that is less than the energy absorbed from the system. If the battery absorbs $P_{B,i}$ in Δt, its charging level is increased by $P_{B,i}\Delta t\eta_{ch}$ and can be stated for $\Delta t = 1$ h as follows:

$$W_i = W_{i-1} + P_{B,i}\eta_{ch} \tag{10}$$

Available energy in the battery is decreased (increased) by $P_{B,i}\Delta t$, which is limited to its maximum value in discharging (charging) mode. The following inequalities represent limitations of discharging and charging rates for the battery, respectively:

$$\left(\frac{(W_i - W_{i-1})}{\Delta t}\right) < P_{Bdch\max} \tag{11}$$

$$\left(\frac{(W_i - W_{i-1})}{\Delta t}\right) > P_{Bch\max} \tag{12}$$

The rate of changes in the output power of the FC is limited to upper and lower boundaries [14], [15]. Therefore, inequalities (13) and (14) are used in the case of increasing or decreasing FC output power, respectively. It should be noted that values of $\Delta P_{FC,U}$ and $\Delta P_{FC,D}$ are not necessarily equal.

$$P_{eFC,i} - P_{eFC,i-1} < \Delta P_{FC,U} \tag{13}$$

$$P_{eFC,i-1} - P_{eFC,i} < \Delta P_{FC,D} \tag{14}$$

TABLE I
ELECTRICITY TARIFF [17]

Period	Time range	Normalized electricity purchase price
Peak	[9,12], [17,22]	1 pu.
Intermediate	[13,16]	0.9 pu.
Off-peak	[1,8], [23,24]	0.78 pu.

The maximum output power of the FC is limited to its nominal capacity. In addition, if FC output power becomes less than a lower threshold, the FC cannot work properly and it should be turned off. The following inequality states constraints of the FC generated power.

$$P_{FC,\min} < P_{eFC,i} < P_{FC,\max} \tag{15}$$

Efficiency of the FC is related to part load ratio (PLR), ratio of electrical generation to maximum FC power rating. The efficiency and ratio of the generated electrical to thermal energy are functions of PLR [16]: when, $PLR_i < 0.05$, the following can be obtained:

$$\eta_{FC,i} = 0.2716; \quad r_{FC,i} = 0.6816 \tag{16}$$

while, $PLR_i \geq 0.05$ then:

$$\begin{aligned} \eta_{FC,i} =& 0.9033PLR_i^5 - 2.9996PLR_i^4 + 3.6503PLR_i^3 \\ & - 2.0704PLR_i^2 + 0.4623PLR_i + 0.3747 \end{aligned} \tag{17}$$

$$\begin{aligned} r_{FC,i} =& 1.0785PLR_i^4 - 1.9739PLR_i^3 + 1.5005PLR_i^2 \\ & - 0.2817PLR_i + 0.6838 \end{aligned} \tag{18}$$

As shown in Fig. 2, FC efficiency is greater in low load operation conditions than the higher PLR [15], [16].

D. Electricity Tariff

In the environment of the electricity market, in order to reduce pressure of the grid peak regulation and realize greater economic benefits, different electricity tariffs have been applied. In other words, electricity tariff is varied in time intervals to moderate behavior of customers in electrical power consumption. In this paper, three different tariffs are considered for electricity price: peak, intermediate, and off-peak tariffs. These tariffs and their corresponding time intervals are listed in Table I [17]. The effects of the electricity tariff on operation costs of the residential energy system are also considered in this paper. All of the tariffs are normalized regarding the maximum electricity tariff defined in the "peak" period. These normalized electricity tariffs are used in (2) as MU_i.

III. IMPERIALISTIC COMPETITION ALGORITHM

CCA is a meta-heuristic method used in non-linear optimization problems [18], [19]. This algorithm is implemented in seven steps described as follows:

A. Step 1: Generating Initial Empires

Similar to other evolutionary algorithms, CCA starts with generating an initial population called "countries." In the N-dimensional optimization problem, where N_{cnt} is total number of countries, the position of the j-th country is determined as follows:

$$Country_j = \left[x_j^1, x_j^2, \ldots, x_j^N\right] \qquad (j = 1, 2, \ldots, N_{cnt})$$

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$P_{B,1}$	$P_{B,2}$	...	$P_{B,24}$	$P_{eFC,1}$	$P_{eFC,2}$	...	$P_{eFC,24}$

Fig. 3. Variables form a country.

In order to determine the dimension of the optimization problem, the number of variables in each time interval should be known. Considering (6), (7) and (18), it is clear that there are two independent variables in each time interval; they are $P_{eFC,i}$ and $P_{B,i}$ because by knowing them and the electrical load demand, the purchased electrical power from the utility is determined using (6). If $P_{eFC,i}$ is known, $P_{hFC,i}$ is determined according to (18). Finally, $P_{gas,i}$ is determined according to (7) using $P_{hL,i}$ and $P_{hFC,i}$. To summarize, using $P_{eFC,i}$ and $P_{B,i}$, all the powers are determined in all parts of the integrated energy system and the costs in equations (1)–(5) can be calculated in each time interval. In this paper, the time interval is equal to $T = 1$ h and the integrated energy system is studied in 24 time sections with two variables in each time interval. Therefore, the dimension of the optimization problem is equal to $N = 24 \times 2 = 48$. Fig. 3 shows a country formed by the optimization variables.

The cost function of the j-th country $(j = 1, 2, \ldots, N_{cnt})$ can be found by evaluating (1) with the variables $(x_j^1, x_j^2, \ldots, x_j^N)$.

Afterwards, N_{imp} of the most powerful countries are selected to form empires and the remaining N_{col} countries will be the colonies belonging to these empires. In the next step, the colonies are divided among the imperialists based on their power. In a minimization problem, powers of the imperialists are inversely proportional to their cost function. The initial number of colonies belonging to an empire is directly proportional to its power. To divide the colonies among the imperialists, normalized costs of the empires are defined as follows:

$$C_n = c_n - \max_i\{c_i\} \tag{19}$$

where c_n is the cost of the n-th imperialist and C_n is its normalized cost.

The power of each imperialist is normalized as follows:

$$P_n = \left| \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i} \right| \tag{20}$$

$$NC_n = round\{P_n N_{col}\} \tag{21}$$

where NC_n is the initial number of colonies belonging to the n-th empire.

For each imperialist, NC_n of the colonies are randomly selected and given to it. These colonies and their imperialist form the n-th empire.

B. Step 2: Moving Colonies Toward Their Imperialists

In this step, the colonies begin to move toward their corresponding imperialists. The positions of the colonies belonging to the n-th empire are updated as follows:

$$new\ col_n^i = col_n^i + rand()\beta\left(I_n - col_n^i\right) \tag{22}$$

where, col_n^i is the position of the i-th colony of the n-th imperialist, I_n is the position of the n-th imperialist, $rand()$ is a function generating a random number between 0 and 1 and β is a weight factor. A random amount of deviation is added to the direction of movement in order to search different points around the imperialist. Movement of the colony toward its imperialist is shown in Fig. 4. A random angle between $(-\gamma, \gamma)$, named θ, adjusts the deviation from the original direction, in which γ is a parameter of the CCA.

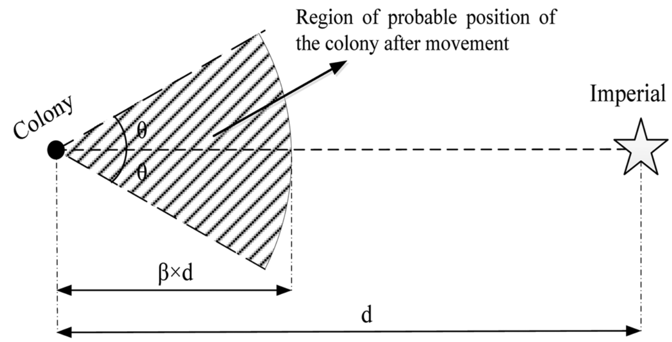

Fig. 4. Movement of a colony toward its imperialist in a randomly deviated direction.

During movement of the colonies, values of $P_{eFC,i}$ and $P_{B,i}$ are changed. In each time interval, all the system constraints should be checked as follows:

a. According to (15), if $P_{eFC,i} < P_{FC,\min}$ or $P_{eFC,i} > P_{FC,\max}$, it is assumed to be equal to $P_{FC,\min}$ or $P_{FC,\max}$, respectively.
b. According to (14), in the case of $P_{eFC,i} < P_{eFC,i-1}$ and $P_{eFC,i} - P_{eFC,i-1} > \Delta P_{FC,D}$, the $P_{eFC,i}$ is considered equal to $P_{eFC,i-1} - \Delta P_{FC,D}$.
c. According to (13), in the case of $P_{eFC,i} > P_{eFC,i-1}$ and $P_{eFC,i} - P_{eFC,i-1} > \Delta P_{FC,U}$, the $P_{eFC,i}$ is considered equal to $P_{eFC,i-1} + \Delta P_{FC,U}$.
d. If the battery is in charging mode $(P_{B,i} < 0)$, the difference between values of $P_{B,i}$ in two subsequent time intervals should not exceed $P_{Bch\max}$; otherwise, $P_{B,i}$ is assumed to be equal to $P_{Bch\max} + P_{B,i-1}$ according to (12).
e. If the battery is in discharging mode $(PB, i > 0)$, the difference between values of the $P_{B,i}$ in two subsequent time intervals should not exceed $P_{Bdch\max}$; otherwise, $P_{B,i}$ is assumed to be equal to $P_{Bdch\max} + P_{B,i-1}$ according to (11).
f. In the charging/discharging mode of battery operation, constraint of maximum/minimum battery energy should be considered. Considering (8), if W_i exceeds these limitations, $P_{B,i}$ should be adjusted to fit the battery energy to maximum or minimum values.

C. Step 3: Updating Position of Imperialists

During the movement procedure, if a colony reaches a position with lower cost than its imperialist, positions of imperialists and that colony are exchanged and the rest of the colonies of this empire move toward the new imperialist position in the next movement process.

D. Step 4: Calculating Total Power of Empire

Total power of an empire depends on powers of the imperialist and its colonies, but it is mainly affected by power of the imperialist. Power of an empire is defined as follows:

$$TP_n = cost(imperialist) + \xi\ mean\{cost(colonies\ of\ empire)\} \tag{23}$$

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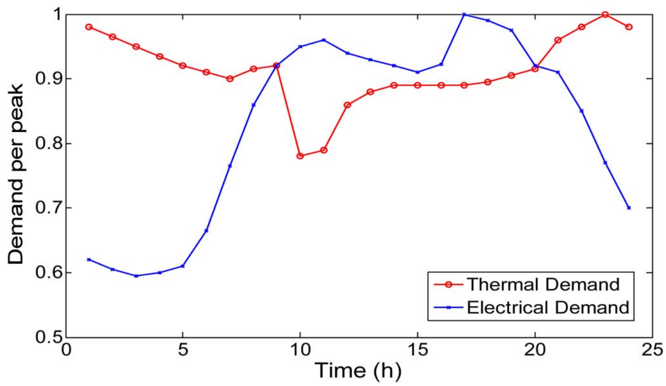

Fig. 5. Daily heat and electricity demand [20].

where ξ representing the role of colonies in determining total power of an empire (TP_n) is $0 < \xi < 1$.

E. Step 5: Imperialistic Competition

In this step, all the empires try to take possession of colonies belonging to other empires. This procedure is called imperialist competition modeled by picking some (usually one) of the weakest empires and competing among all empires to possess the colonies. Empires compete for taking possession of these colonies based on their total powers. Therefore, a powerful empire has a higher chance of possessing the mentioned colonies. To model the competition process, the normalized total power (NTP) of each empire is calculated as follows:

$$NTP_n = TP_n - \max_i\{TP_i\} \tag{24}$$

Then, possession probability of the n-th empire, ps_n is given by the following equation:

$$ps_n = \left| \frac{NTP_n}{\sum_{i=1}^{N_{imp}} NTP_i} \right| \tag{25}$$

F. Step 6: Eliminating Powerless Empires

Different criteria can be defined for the empire collapse mechanism. Powerless empires will collapse in the imperialistic competition. An empire is assumed to collapse when it loses all of its colonies.

G. Step 7: Convergence

After some imperialistic competitions, all the empires will collapse, except for the most powerful one, and all the countries become colonies of this empire. There are no differences among the colonies and their imperialists. All the colonies have the same positions and the same costs. In such a case, the algorithm ends.

IV. Simulation Results and Discussion

The variations of the normalized values of thermal and electrical demands are shown in Fig. 5 [20]. As illustrated in this figure, during a day, demand of thermal load is stable to a certain extent and shows changes in the range of 80%–100% whereas the electrical demand is more fluctuating (up to 40%) [20]. Fig. 5

TABLE II
Parameters of System [6]

FC startup cost, α_1 (\$)	0.15
Maximum limit of FC power, $P_{FC,\max}$ (kW)	1.2
Minimum limit of FC power, $P_{FC,\min}$ (kW)	0.05
Upper limit of ramp rate of FC, $\Delta P_{FC,U}$ (kW)	0.75
Lower limit of ramp rate of FC, $\Delta P_{FC,D}$ (kW)	0.9
FC shutdown cost, α_2 (\$)	0
Initial energy in battery, W_{init} (kWh)	0
Charging efficiency of battery, η_{ch} (pu.)	0.927
Discharging efficiency of battery, η_{dch} (pu.)	0.971
Maximum energy in battery, $W_{\max}$ (kWh)	3
Minimum energy in battery, $W_{\min}$ (kWh)	0
Upper limit of battery charging rate, $P_{Bch\max}$ (kW)	-0.75
Upper limit of battery discharging rate, $P_{Bdch\max}$ (kW)	2.25
Length of time interval, T (h)	1
Operation and maintenance cost of battery, C_{B_b} (\$/kW)	0
Cost of purchasing natural gas, C_{gas_b} (\$/kW)	0.05
Cost of purchasing electricity from utility, C_{U_b} (\$/kW)	0.13

TABLE III
CCA Parameters

Number of imperialists, N_{imp}	20
Number of colonies, N_{col}	1000
Role of colonies in empire total power determining, ξ	0.1
Weight factor of colonies movement, β	2
Maximum deviation angle from the original direction, γ	π/4

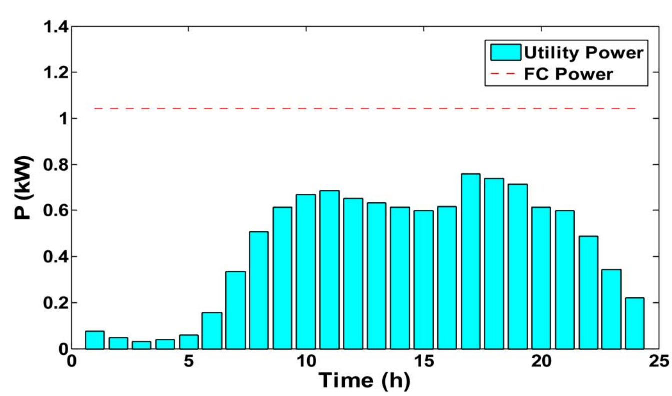

Fig. 6. Optimized power dispatch for main grid (bar chart) and FC (dashed line).

is selected in this paper as the demand curves to make the results comparable with [6]. The peak of heat and electricity demands are 2 kW and 1.8 kW, respectively [6].

Parameters of the under study system and CCA parameters are given in Tables II and III, respectively. The simulation is carried out for two different scenarios.

Scenario 1: Base Case: In this case, no battery is used and different electricity tariffs are not considered. The electricity tariff is assumed to be constant and equal to 0.13\$/kW. Results of the optimized power dispatch for CHP and the main grid are determined using CCA and are shown in Fig. 6.

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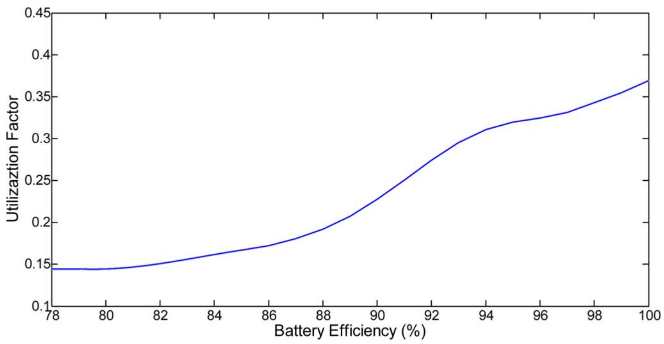

Fig. 7. The smoothed curve of effect of battery efficiency changes on UF value.

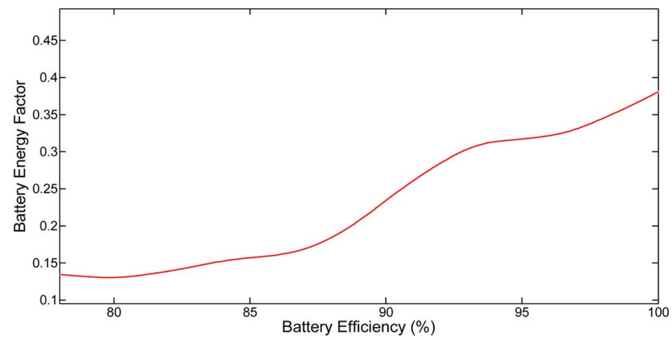

Fig. 8. The smoothed curve of effect of battery efficiency changes on BEF value.

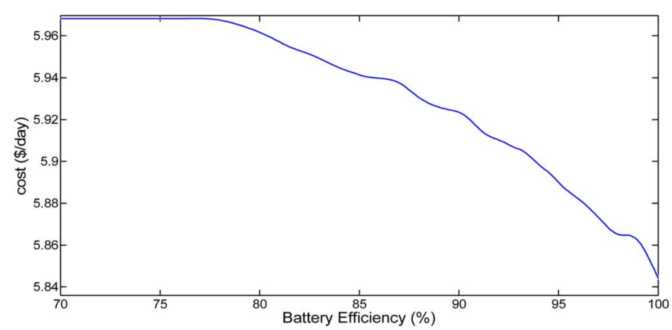

Fig. 9. The smoothed curve of effect of battery efficiency on operating cost.

As expected, FC works at almost its maximum limit of power generation because the tariff of purchasing electrical power remains constant in 24 hours and the main grid's electrical cost is more than the FC electrical cost. In other words, since the gas price is significantly less than electricity, the CHP generates the electricity at almost its maximum limit. FC does not work exactly at its maximum level and the optimal value of the FC generation is equal to 1.041 kW. As shown in Fig. 2, if FC generates more electrical power, its efficiency is decreased and its generation cost becomes higher than the utility cost. In this scenario, the total cost of the system is 5.9947 ($/day) according to (1) while $\sum C_{B,i} = 0$ and $MU_i = 1$. The total cost of 6.38 ($/day) has been attained in [6] using HSA. Then, better performance of using CCA can be seen here.

If different electricity tariffs are not considered, the battery will not cooperate in energy balance because costs of the main grid's electrical energy for battery charging and discharging are the same. This scenario is like a region that has the small difference in the electricity tariffs.

Scenario 2: Considering the Battery and Electricity Tariff: Different electricity tariffs and the battery are considered in this scenario. Thus, it is expected that the proper scheduling among different sources and the battery can lead to a major decrease in the system operating costs.

It should be mentioned that regarding the value of electricity price in peak and off-peak periods (Table I), if the efficiency of the battery is less than 78%, the battery does not cooperate in energy saving or energy generation. Therefore, the lowest efficiency of battery is determined by the electricity tariff assumption. If large price differential is assumed in the electricity tariff, the battery efficiency can go lower and the battery will still help to reduce the total cost of meeting the demand of the smart house. Suppose that the battery efficiency is equal to 78%. If the battery absorbs 1 kW active power in the low-cost period with a cost of 0.78 pu/kW, it can deliver $1 \times 0.78 = 0.78$ kw to the system during the high-cost period with 1 pu/kW.

It should be noted that, in the mentioned example, the battery is charged in the low-cost time period with efficiency of η_{ch} and discharged in the high-cost time interval with efficiency of η_{dch}. Therefore, a lower limit of $\eta_{ch} \times \eta_{dch}$ is 78%. If the product of the charging and discharging efficiencies is lower than 78%, the battery does not affect the energy routing in the system and its power is equal to zero for all the time intervals as described in scenario 1. The term "battery efficiency" in this section indicates $\eta_{ch} \times \eta_{dch}$.

In order to assess effectiveness of the battery usage in the system, the following index, called utilization factor (UF), is defined:

$$UF = \frac{P_{ave}}{P_{\max}} \tag{26}$$

As expressed in (26), UF assesses flatness of the active power generated by the battery in a day. A lower value of UF shows that the battery generates/absorbs a high amount of electrical power only in a few time intervals. A UF value close to 1.0 shows effectiveness of the battery and better usage of its capacity in the hybrid energy system in all the time intervals. As shown in Fig. 7, higher battery efficiency makes UF closer to 1.0.

To assess the role of the battery in the energy system and show its cooperation in the system, the following index, called battery efficiency factor (BEF), is defined:

$$BEF = \frac{Battery\ total\ energy}{(24P_{\max})} \tag{27}$$

BEF shows the ratio of the generated/absorbed energy in a day to the maximum capacity of the battery.

Since the battery can charge/discharge with the maximum rate of $P_{\max}$, the maximum of its total available capacity is $24P_{\max}$. As shown in Fig. 8, higher battery efficiency leads BEF to become closer to 1.0.

As demonstrated in Fig. 9, the operating cost of the system is decreased with an increase in the battery efficiency. As mentioned before, if the battery efficiency is less than 78%, it does not cooperate in energy saving. Therefore, the cost of the system is constant in this case and equal to scenario 1, in which the battery has not been considered.

The results of the cost minimization using CCA are shown in Figs. 10 and 11. Power generations of different sources and the battery state of charge are shown in Fig. 10. In this figure, the battery efficiency is assumed to be equal to 0.9. Negative and positive $P_{B,i}$ indicate the battery charging and discharging modes, respectively.

As shown in Fig. 10, depending on different electricity tariffs, the CHP electrical generation varies to decrease its generation cost in each time interval compared to the utility cost. Variations of the FC power generation considering its efficiency are shown

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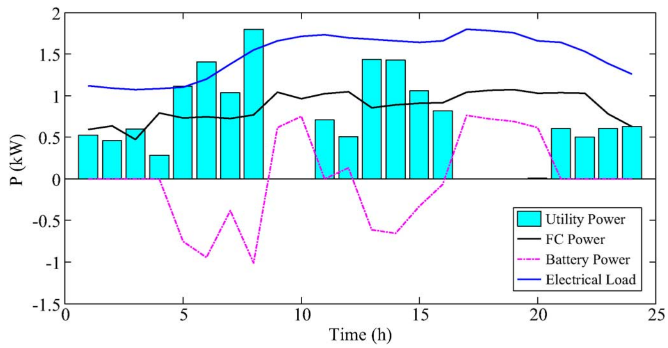

Fig. 10. Optimized generations schedule for scenario 2 (battery efficiency is 0.9).

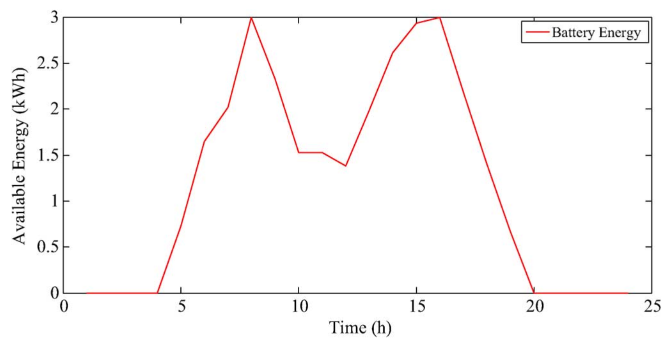

Fig. 11. Battery energy for scenario 2.

in Fig. 2. It can be seen that the higher electricity tariff causes higher FC generation. As demonstrated in Fig. 11, the battery is charged in the off-peak period in order to gain the ability of discharging in the peak period when the electricity tariff is at the highest level.

In the first eight intervals, the battery is charged by the utility because the utility electrical cost is at its lowest level. FC does not generate its maximum output power because it should generate the amount of power such that its cost becomes less than the utility. In other words, if FC generates more power, its efficiency is reduced and it causes higher cost compared to the utility cost. Similar to the first eight intervals, in the 13th to 16th intervals, the battery is re-charged and maximum available energy is obtained in the 16th interval.

In the 9th to 12th and 17th to 22th intervals, the electricity tariff is in the peak period. Therefore, the battery delivers all of its stored energy into the energy system and FC generates the power almost at its maximum limit (not exactly at the maximum level as described in scenario 1).

All the optimized generations, electrical and thermal demands and all of their optimal costs with the assumption of battery efficiency of 0.9 are listed in Tables IV and V, respectively. For different gas prices and electricity tariffs, the results can be changed.

In this scenario, the total cost of the system is 5.92 ($/day) according to (1) which is better than 5.98 ($/day) attained in [6] using HSA. It should be noted that this is an offline study and this optimization is done one day ahead. Therefore, run times of optimization algorithms are not important for this study. However, these algorithms have been run in the same computer and their run times have been compared. It takes 9.80 seconds and 6.25 seconds to run the CCA and HSA, respectively. CCA needs a 20 × 48 variable matrix for its empires and HSA needs a 10 × 48 variable matrix for its HM. As presented in the paper, CCA obtains less total cost than HSA.

TABLE IV
SOURCE GENERATIONS, ELECTRICAL AND THERMAL DEMAND

Interval (Hour)	$P_{eL,i}$ (kW)	$P_{eFC,i}$ (kW)	$P_{B,i}$ (kW)	$P_{U,i}$ (kW)	$P_{hL,i}$ (kW)	$P_{gas,i}$ (kW)
1	1.12	0.59	0	0.52	1.96	1.52
2	1.09	0.63	0	0.46	1.93	1.46
3	1.07	0.47	0	0.60	1.9	1.56
4	1.08	0.79	0	0.29	1.87	1.24
5	1.1	0.73	-0.75	1.11	1.84	1.27
6	1.20	0.74	-0.95	1.40	1.82	1.24
7	1.38	0.72	-0.38	1.04	1.8	1.24
8	1.55	0.77	-1.01	1.79	1.83	1.23
9	1.66	1.04	0.62	0	1.84	0.92
10	1.71	0.96	0.75	0	1.56	0.74
11	1.73	1.02	0	0.71	1.58	0.68
12	1.69	1.05	0.13	0.51	1.72	0.78
13	1.67	0.86	-0.62	1.43	1.76	1.07
14	1.66	0.89	-0.66	1.43	1.78	1.05
15	1.64	0.91	-0.3	1.06	1.78	1.03
16	1.66	0.91	-0.07	0.81	1.78	1.02
17	1.80	1.04	0.76	0	1.78	0.85
18	1.78	1.07	0.72	0	1.79	0.83
19	1.76	1.07	0.69	0	1.81	0.84
20	1.66	1.03	0.62	0.01	1.83	0.93
21	1.64	1.03	0	0.60	1.92	1.00
22	1.53	1.03	0	0.50	1.96	1.05
23	1.39	0.78	0	0.60	2	1.39
24	1.26	0.63	0	0.63	1.96	1.49

TABLE V
SOURCE GENERATION COSTS

Interval (Hour)	Gas cost ($/day)	CHP cost ($/day)	Utility cost ($/day)	Total cost ($/day)
1	0.08	0.08	0.05	0.21
2	0.07	0.08	0.05	0.20
3	0.08	0.06	0.06	0.20
4	0.06	0.11	0.03	0.20
5	0.06	0.10	0.11	0.27
6	0.06	0.10	0.14	0.30
7	0.06	0.10	0.11	0.26
8	0.06	0.10	0.18	0.35
9	0.05	0.15	0	0.20
10	0.04	0.13	0	0.17
11	0.03	0.15	0.09	0.27
12	0.04	0.15	0.07	0.26
13	0.05	0.12	0.17	0.34
14	0.05	0.12	0.17	0.34
15	0.05	0.13	0.12	0.30
16	0.05	0.13	0.09	0.27
17	0.04	0.15	0	0.19
18	0.04	0.16	0	0.20
19	0.04	0.16	0	0.20
20	0.05	0.15	0	0.20
21	0.05	0.15	0.08	0.28
22	0.05	0.15	0.07	0.27
23	0.07	0.105	0.06	0.24
24	0.07	0.08	0.06	0.22
Total Cost				5.92

By comparing operating costs in the two mentioned scenarios (5.9947$ and 5.92$) it is obvious that usage of the battery has an advantage in the case of considering electricity tariff. The gathered data in Table IV can be used as a look-up table to determine power generation of different sources and state of charge of the battery in each time interval to have the minimum system operation cost. In other words, the results of this paper can be used by the energy management system as a look-up table to dispatch the electrical and thermal power in each time interval.

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V. Conclusion

Economic operation of the hybrid home energy system composed of a FC and a battery connected to the utility has been studied in this paper. Based on deterministic prediction of electrical and thermal power demands and utility prices, an optimization model has been established. The energy routing of this system has been investigated in order to optimize the system operation costs. Effects of the battery efficiency and electricity tariff on the system operation cost are illustrated in the simulation results. The comparison of two different scenarios indicates that optimal scheduling of electrical and thermal generations can decrease the system operation costs. In other words, a look-up table can be prepared and used for a smart home with hybrid energy system in order to decrease operation cost.

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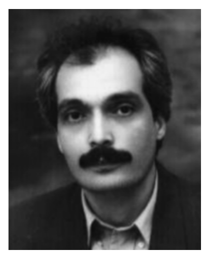

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