Energy Management of a Smart Home Micro Grid in Presence of Micro-CCHP

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***Abstract*— The micro grid studied in this paper supplies a residential building in a region with hot weather. The main distribution system source which is the focal point of this study is a micro-CCHP unit. Along with this source, photovoltaic Cells and the battery of a hybrid electric car are used respectively as the renewable energy and an electric energy storage source. In fact, by employing mathematical relations regarding micro-CCHP units this possibility is provided to study micro-CCHP units in a smart energy management system and observe their function in the presence of other distribution system sources. In addition to the heat load that provides the buildings required hot water, supplying the desired temperature of the building in hot seasons by adding an absorption chiller and adding cool load is studied and simulated. This kind of detailed modeling of heat and cool load intensifies the possibility of a better coordination between heat, cool and the output electric power of micro-CCHP which results in the optimal control and utilization of it.**

***Index Terms*—Micro-CCHP, Load Response, Heat-Led Control, Time of Use (TOU), Real Time Pricing (RTP).**

I. Introduction

Rapidly rising energy prices, limited supply of fossil fuels, concerns about environmental issues, global warming and transmission losses have led to a focused attention to micro grids in which distributed generation systems are designed for higher energy efficiency than conventional systems. Microgrids are low voltage distribution networks which consist of micro sources, distributed generators (DGs) and storage devices. Along with different thermal and electrical controllable loads which can be connected to the main grid or operate in island mode. The small scale distributed generators involve several technologies such as Micro Turbines (MTs), Fuel Cells (FCs), Wind Turbines (WTs), Photovoltaics (PVs) and micro-Combined Heat and Power generation (Micro-CHP) [1]. Using DG systems can provide significant environmental benefits and increase the energy efficiency by employing renewable primary energy, diminishing electricity transport losses and cogeneration options [2, 3].

In recent years micro-CHP systems have been discussed in many researches [6, 7]. A micro-CHP system is an energy conversion unit with an electric capacity below 15 kW that simultaneously generates heat and power from a single primary energy source [4]. Based on this definition, micro-CHPs are relatively small and can be the same size as conventional heating systems like water heaters. This system captures waste heat during electricity generation process to provide thermal loads and improves overall system efficiency. Therefore, the cost of thermal energy production is reduced. The common fuel of a micro-CHP system is natural gas. So, in the near future, these systems can be used as the next generation of domestic heating systems for countries with large scale natural gas infrastructure such as the Netherlands, Germany, Italy, Canada, United States, Japan and Iran [5-7]. A typical micro-CHP system includes a main fossil fuel based prime mover coupled with a generator, a heat exchanger and an auxiliary burner.

As mentioned before, micro-CHP units can provide electrical and thermal energy for residential buildings but in regions with hot weather a significant part of the required energy is the cool load which imposes a great cost on the micro grid. On the other hand, the heat load in these regions is on its minimum in the hot seasons and using micro-CHP is not cost-effective. In the past years CHP systems which can produce heat and power are widely used in the hotels, hospitals and commercial buildings but in the recent years extensive researches on micro-CCHP have been carried out. The difference between micro-CHP and micro-CCHP is that the output heat from the process of producing electric power, in addition to supplying the required heat, supplies the cool load by thermal active equipment [8, 9]. Since the output thermal power of the prime mover in micro-CCHP systems is low, thermal active equipment used in these systems are usually single effect absorption chillers and surface absorption chillers [10, 11]. One of the most salient points which has great importance in micro-CHP systems, is the methods of controlling micro-CHP unit and coordination of heat and electric loads. Generally, control methods are divided into smart and non-smart methods. In non-smart methods the output power of micro-CHP is set on a specified value for electric and heat, but in smart methods the output power can be variable in a span to minimize the operation cost of micro-grid. In different sources they came up with solutions to smarten control strategies. [12] has implemented load response by using variable heat loads in a micro-CHP system, to create a better coordination between the loads and lower the micro-CHP operating cost significantly compared to non-smart control [13]. In addition, using variable heat loads improved the coordination between heat and electric loads by adding smart measurements to the micro grid. In this research, electric loads are divided into shiftable and non-shiftable loads and an

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optimization module coordinate electric and heat loads simultaneously considering the TOU network tariffs. In micro-CCHP systems by adding cool loads to the micro grid coordination between these three loads gets more important but studies concerning these systems are often based on laboratory studies and the evaluation of the performance of these systems in terms of thermal and mechanical properties [10, 11, 14, 15]. In fact, the performance of these systems in smart grids and micro grids, as well as the effect of coordination of these three loads on the costs of the micro grid, has not been studied. In this paper, considering a smart home micro grid in a region with hot weather, providing the electric, heat and cool loads, coordination between them and energy management in the aforementioned micro grid has been studied. Moreover, the effect of smartening the micro grid on its operating cost has been analyzed simultaneously with TOU and RTP tariffs. One of the other issues considered in this study is the variability of the heat and electric efficiency of the micro-CCHP unit. In the previous studies such as the references [12, 13, 16], these two efficiencies are assumed to be constant in different loads (varying from minimum to full load). This assumption is inaccurate and far from reality because in practice, with the increment of the load of the micro-CHP unit, the electric efficiency increases and the heat efficiency decreases and vice versa. In this study, the mathematical relation between these two efficiencies has been updated by actual heat and electric efficiency of the micro-CHP units which work based on the internal combustion engine. This is done by linear approximation concerning the actual heat and electric efficiency of an actual micro-CHP [17].

II. Ease of Use Micro-CCHP Economic Performance Under non-smart Control

Several references have discussed the control strategies of micro-CHP and micro-CCHP units. Reference [18] has made a good overview of the design of control strategies for micro-CHP units. This reference has divided these strategies into two general categories of heat-led and electricity-led, which their purpose is to provide a constant and predetermined supply of heat and electric load, respectively. Different modes of utilizing various types of micro-CCHP systems are presented in [9]. Also a review of existing technologies in the field of micro-CCHP has been performed. In this reference three of the different types of technologies available for the micro-CCHP systems, including thermal pump technology, thermal pump with electric actuator and thermal pump with heating actuator are defined and triple operation modes for providing electric, heat and cool loads are presented separately.

In order to demonstrate the effect of smartening micro-CCHP control as well as the effect of other technologies on the cost of grid utilization, a standard reference for smart and non-smart comparison should be presented. To achieve this goal, the micro-CHP unit standard control strategy presented in reference [19] has been used. To simulate and control micro-CCHP in a non-smart method, the heat and cool load required for the micro grid should be calculated and formulated instantaneously. For this purpose, the water temperature of the hot water tank connected to the micro-CCHP unit and the ambient temperature inside the building should be constantly controlled. As shown in Fig.1, two factors that reduce the temperature of the hot water of the tank are hot water consumption of the building, and the hot water needed to provide the heat necessary for the absorption chiller. As the hot water drains out of the tank, cold water enters it. This way, you can control the energy level of the storage source to provide the required heat.

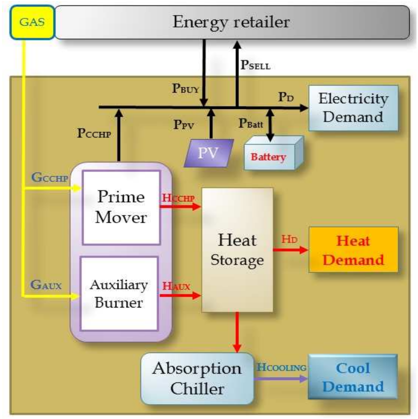

Figure 1: Energy flows in the household-retailer system

The water temperature of the storage tank is obtained by the following proposed equation:

$$T_{st}(h+1) = \frac{V_{cold}(h)\left(T_{st\text{-}cold} - T_{st}(h)\right) + \left(V_{total}.T_{st}(h)\right)}{V_{total}} + \frac{H_{cooling}(h) - H_{air}(h)}{V_{total}.C_{water}} \quad (1)$$

In which, $V_{cold}(h)$ and $T_{st\text{-}cold}$, respectively, are the volume and temperature of cold water entering the tank, V_{total} the total volume of the hot water tank, $H_{cooling}(h)$ the heat requirement of the absorption chiller to compensate for the heat entering the building, and $H_{air}(h)$ the heat power entering the building due to the heat outside. The amount of this heat is obtained by the following equation:

$$H_{air}(h) = \frac{T_{in\text{-}desired} - T_{out}(h)}{R} \quad (2)$$

In the warm seasons $H_{air}(h)$ is negative due to the higher outdoor temperature. This means that thermal energy enters the wall of the building and causes the interior space to warm up, so the absorption chiller should produce the same amount of cooling. To provide this cooling rate, the thermal energy required by the absorption chiller should be calculated by the equation (3).

$$H_{cooling}(h) = \frac{H_{CCHP}(h) + H_{aux}(h)}{COP_{chiller}} \quad (3)$$

In which $H_{CCHP}(h)$ and $H_{aux}(h)$ are, respectively, the heat power output of the micro-CCHP unit and the auxiliary water heater and $COP_{chiller}$ is the coefficient of performance of the absorption chiller.

The amount of $COP_{chiller}$ depends on a number of factors, including technology, type of chiller and the temperature of the hot water entering it, and is calculated by the following equation:

$$COP_{chiller} = \frac{Q_{refrigeration-Power}(h)}{Q_{chiller-Heating-Power}(h)} \quad (4)$$

Considering this equation, it is clear that this coefficient varies with the changes of the input heat to the chiller, but if we can control the temperature of the inlet to the chiller, which is the temperature of the hot water, within a certain range, the coefficient can be assumed to be constant with an acceptable approximation. To control the micro-CCHP system in the non-smart control strategy, indoor temperature and hot water temperature inside the tank should be controlled at 25 and 80°C, respectively. In this paper based on reference [20] the standard control called "heat-led" is used to control the hot water temperature inside the tank to adjust the inside temperature of the building and the hot water temperature.

In this paper, it is assumed that the prime mover is an internal combustion engine type, and its switching on / off speed is high, therefore, the equation of the power gradient of the micro-CHP unit, called *ramp rate*, is ignored. Also, since the CCHP heat output is enough to provide the heat load of the building and chiller, no auxiliary boiler has been used to aid in simulations.

III. Micro-CCHP Smart Predictive Control

In the heat-led and cool-led control strategies, only the heat and cooling charges of the grid are tracked and other issues such as cost is not considered. Consequently, this control method has weaknesses that lead to an increase in the cost of grid utilization. The reason for the increase in costs is that, when the grid utilization tariff is high and the heat load is at a low level, the supply of electric load through the main grid inflicts a great cost on the micro grid. On the contrary, when the electricity tariff is low and the heat load of the micro grid is high and micro-CCHP is forced to generate high heat power, the micro grid cannot sell its output electrical power to the main grid at a suitable price. With predictive smart control, it is possible to predict the future of the micro grid, and then, with the implementation of the load response program, significantly reduce the cost of micro grid utilization. A predictive controller is connected to the micro-CCHP unit and a smart meter is tasked with receiving price information from a power company from the previous day. Using the smart metering infrastructure, the algorithm programmed by the digital control system is applied to the micro grid and the controller's task is to determine the time and amount of micro-CCHP power production, in a way that minimizes the cost of the operation of the micro grid while taking into account the operating constraints.

Considering that the micro-CCHP unit has many constraints discussed in Section 4, the optimal control issue is solved using the predictive method. In this sense, the control issue with a finite horizon is optimized at any time-step.

The predictive control strategy is usually discretized in time in a way that in every time-step an optimization problem is solved. In this strategy, first, a target function specifies the desired operation and describes a predictive model based on it. Then, the relevant constraints are applied to provide limitations for the standard performance of the micro-CCHP system. The predictive controller's goal is to determine the operations which, based on the objective function, lead to optimization of the system's behavior [21, 22]

IV. Formulation

A. The objective function

The objective function in this issue is to minimize the cost of micro grid utilization, which is the cost of the gas consumed by the micro-CCHP unit and the electricity purchased from the main grid. The cost function J is defined as:

$$J = \sum_{h=1}^{24}\Big[\big(Tariff(h).P_{grid}(h)\big) + G_p.\big(G_{CCHP}(h) + G_{aux}(h)\big)\Big] \quad (5)$$

In which $Tariff(h)$ is the tariff of the electricity purchased/sold from/to the grid, $P_{grid}(h)$ is the power transmitted between the main grid and the micro grid, $G_{CCHP}(h)$ is the gas consumption of the micro-CCHP unit, $G_{aux}(h)$ is the gas consumed by the auxiliary water heater at hour and G_P is the price of natural gas.

Considering that the designated prime mover is an internal combustion engine, the cost of the gas consumed at start-up is ignored. Moreover, its heat power capacity is high enough that no auxiliary boiler is used.

Regarding equation (5), it can be seen that the electric power purchased / sold from / to the grid at any given time is equal and the cost of gas is always considered constant.

B. Electric and heat efficiency

In the majority of references like [16, 20, 23], the output heat and electric efficiency of the micro-CHP unit is assumed to be constant, but in reality these two efficiencies are not constant, and there are many variations in the efficiency from no load to the nominal load. As a result, in this paper, these two efficiencies are approximated using the information of an actual micro-CHP as follows:

$$\begin{aligned} \eta_e(h) &= 0.2145 + \big(0.055 \times Load(h)\big) \\ \eta_{th}(h) &= 0.50667 - \big(0.0667 \times Load(h)\big) \end{aligned} \quad (6)$$

In which η_e and η_{th} are the electric and heat efficiency respectively, and $Load(h)$ is the percentage of electric load at hour h which is obtained by:

$$Load(h) = \frac{P_{CCHP}(h)}{P_{CCHP-max}} \quad (7)$$

In which $P_{CCHP}(h)$ is the electric power of the micro-CCHP unit at hour h and $P_{CCHP-max}$ is its maximum electric power.

C. Constraints

Limitations to be imposed by the predictive controller are defined as constraints for it. These constraints consist of a set of relations and limitations that operate and control the overall micro grid and micro-CCHP unit in a proper state.

1) Electric and heat power

One of the most important constraints that exist in micro-CCHP units is the electric, heat and cool power output that should be between the minimum and maximum limits. The range of electric power ($P_{CCHP}(h)$) and heat power of the prime mover ($H_{CCHP}(h)$) is always between a given value. Also, by introducing the binary variable $V_{CCHP}(h)$ that indicates whether micro-CCHP is turned on or off at hour h , we will have:

$$\begin{aligned} P_{CCHP\text{-}min}.V_{CCHP}(h) \le P_{CCHP}(h) \le P_{CCHP\text{-}max}.V_{CCHP}(h) \\ H_{CCHP\text{-}min}.V_{CCHP}(h) \le H_{CCHP}(h) \le H_{CCHP\text{-}max}.V_{CCHP}(h) \end{aligned} \tag{8}$$

In which $P_{CCHP\text{-}min}$ and $P_{CCHP\text{-}max}$ are the minimum and maximum electric output power, $H_{CCHP\text{-}min}$ and $H_{CCHP\text{-}max}$ are the minimum and maximum output heat power of the micro-CCHP.

Since cool power is a function of the heat output, there is no need to restrict it.

2) Hot water temperature of the water tank

To implement the load response program which was mentioned in part 3, a range should be considered for the heat load. As a result, the water temperature in the storage tank at hour will be as follows:

$$T_{st\text{-}min} \le T_{st}(h) \le T_{st\text{-}max} \tag{9}$$

In the above equation $T_{st\text{-}min}$ and $T_{st\text{-}max}$ are the minimum and maximum water temperature of the storage tank respectively.

Since the absorption coefficient of the chiller changes with the variation in the water temperature of the storage tank, in order to be able to consider the chiller efficiency constant the temperature range should be very low. Considering this limitation, the hot water consumption of the micro grid (the building) is provided at a suitable and acceptable temperature. In this paper, the coefficient of efficiency of the chiller is assumed to be constant and equal to 0.4.

3) Indoor temperature constraint

As mentioned before, the micro grid is designed for a region with hot weather. The ambient temperature inside the building is provided by the cold water outlet of the chiller and a fan coil system, which must be within a specified range to achieve consumer comfort. As a result we will have:

$$T_{in\text{-}min} \le T_{in}(h) \le T_{in\text{-}max} \tag{10}$$

In which $T_{in\text{-}min}$ and $T_{in\text{-}max}$ are respectively the minimum and maximum temperature inside the building. The constraints 9 and 10 are constant in the non-smart control in the following way:

$$\begin{aligned} T_{st}(h) = T_{st\text{-}des} \\ T_{in}(h) = T_{in\text{-}des} \end{aligned} \tag{11}$$

In which $T_{st\text{-}des}$ and $T_{in\text{-}des}$ are respectively the optimum temperature of the water in the tank and the inside of the building.

Due to the fact that the prime mover technology is considered to be an internal combustion engine, the response rate to power changes in this technology is high, therefore, the power output slope is ignored.

4) Micro grid electric load constraints

The total electric power generated by distributed generators per hour should be equal to the electric power required by the micro grid (P_{Demand}). In this case, we will have:

$$P_{CCHP}(h) + P_{PV}(h) + P_{Batt}(h) + P_{Grid}(h) = P_{Demand}(h) \tag{12}$$

Where $P_{Grid}(h)$ is the purchased/sold power from/to the local grid at hour h. $P_{PV}(h)$ is the output power of PV panels and $P_{Batt}(h)$ is the Battery's net output power at hour h.

Considering the load shift, the balance constraint is as follows:

$$P_{CCHP}(h) + P_{PV}(h) + P_{Batt}(h) + P_{Grid}(h) = P_{d\text{-}nsh}(h) + \sum_{n\text{-}1}^{Nsh} P_{d\text{-}sh}^{n} \tag{13}$$

Where $P_{d\text{-}nsh}(h)$, is the total power consumption of nonshiftable loads at hour h and $P_{d\text{-}sh}^{n}$ is the power consumption of n^{th} shiftable load at hour (h) and N_{sh} is the number of existing shiftable loads.

5) Battery related constraints

In this paper, it is assumed that a Plug-in hybrid electric vehicle (PHEV) with the specifications specified in reference [24] is connected to a micro grid which is parked in the building. The battery power at hour $P_{Batt}(h)$ can be in one of these three states: charging, discharging and idle. If the battery is charging and discharging, the capacity of the outlet and input power of the battery cannot exceed its maximum. In other words, it is not possible to recharge or discharge the battery all at once or with any given power:

$$P_{batt\text{-}ch}(h) \le P_{ch\text{-}max} \tag{14}$$

Where $P_{batt\text{-}ch}(h)$ is the input power to the battery (charge) at hour h and $P_{ch\text{-}max}(h)$ is the maximum power of the battery can be charged with.

The same is true for the discharge power of the battery:

$$P_{batt\text{-}dch}(h) \le P_{dch\text{-}max} \tag{15}$$

The socket capacity which the PHEV is connected to it is 1.4 kW. As a result, the maximum and minimum charge and discharge capability is equal to this value [1]. Another important parameter in battery performance is the battery's state of charge.

$$SOC_{min} \le SOC(h) \le 1 \tag{16}$$

In which SOC_{min} is the minimum battery charge to improve the lifetime of the battery.

Hourly change of the battery charge status is as follows:

$$SOC(h+1) = SOC(h) + \frac{P_{batt}(h)}{E_{batt}} \quad (17)$$

$$P_{batt}(h) = P_{batt\text{-}ch}(h) + P_{batt\text{-}dch}(h) \quad (18)$$

Where E_{batt} is the total capacity of the battery and $P_{batt}(h)$ is the battery power at hour h . Also, $P_{batt\text{-}ch}(h)$ and $P_{batt\text{-}dch}(h)$ are the power of charging and discharging the battery at hour h respectively.

6) Constraints related to shiftable loads

In order to implement the load shift program, it is assumed that to use the electrical equipment $x(n)$ which is referred to as the shiftable load, the user specifies the total hours that the equipment can be used. On the other hand, the predictive module, according to information from advanced metering infrastructure (AMI), predicts that the $x(n)$ shiftable load will consume energy $(E_n(kWh))$ in hours of operation (HOP_n) over the next day. With this information, the following constraints should be considered for these loads as below:

$$P^{n}_{d\text{-}sh}(h) = \frac{E_n}{HOP_n}.W_n(h) \quad (19)$$

$W_n(h)$ is the operation state of n^{th} shiftable load at hour (h) ; 1: on, 0: off.

V. Simulation results

As discussed in Section III, using a predictive controller, energy management was implemented in a smart home micro grid with a micro-CCHP unit. This micro grid is located in a region with hot weather in order to have electric, heat and cool loads in the micro grid simultaneously. The capacity of the hot water storage tank is considered to be *150* liters, and a photovoltaic system with a nominal output of 1.1 kilowatts of electricity will inject power into the micro grid, according to Fig. 2. There is a PHEV electric vehicle battery with a power of *86.6 kW/h* as in reference [24] and the performance of the battery in case 3 is presented in Fig.3.The electric demands of the micro grid are shown separately in Fig.4. In which each users share is determined by smart measuring, and the shiftable loads are shown in Table.1.

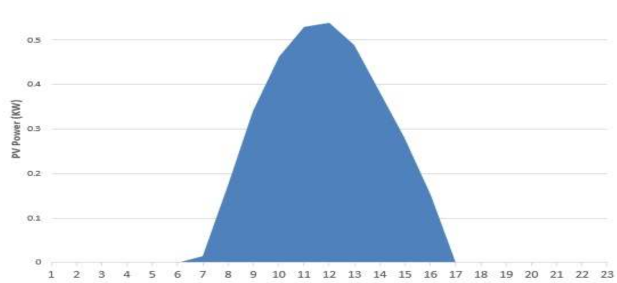

Figure 2. Photovoltaic system electrical output power

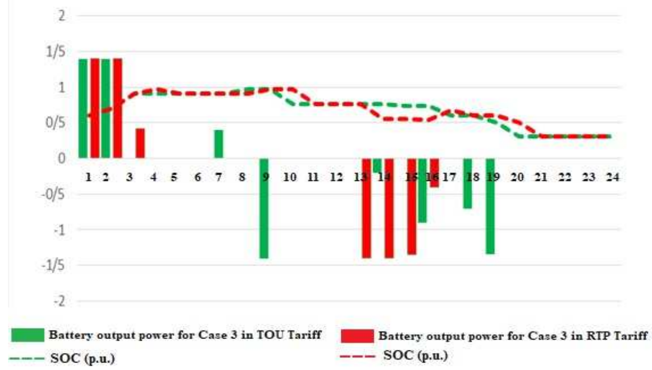

Figure 3. Battery output power and SOC for Case 3

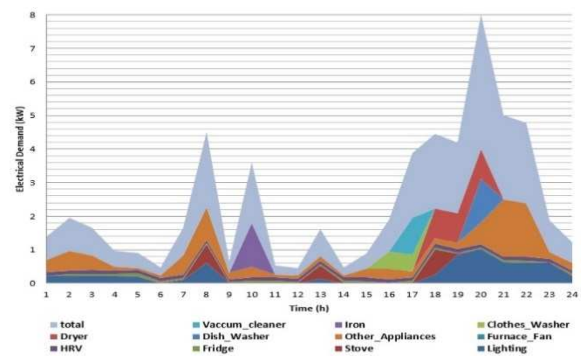

Figure 4. Total electrical demand showing each appliance's share.

TABLE I. SHIFTABLE DEMAND DATA

Shiftable load	Energy usage E_n *(kWh)*	Operation time HOP_n
Spin-drier	1	2
Blotter	2.7	3
Iron	1.3	1
Dishwashing Machine	1.3	1
Vacuum cleaner	1.1	1

To illustrate the impact of micro grid smartening on its cost, five operating cases have been simulated and the results have been compared and presented. These cases are introduced in Table.2

TABLE II. SIMULATED CASES

Feature \ Case	1	2	3	4	5
Smart Control		✓	✓	✓	✓
Battery			✓	✓	✓
PV				✓	✓
Demand Response					✓

Fig. 5 shows the electrical demand profile before and after load shifting and Fig. 6 shows the operation cost of utilizing grid based on these five scenarios in both TOU and RTP tariffs (Table.3).

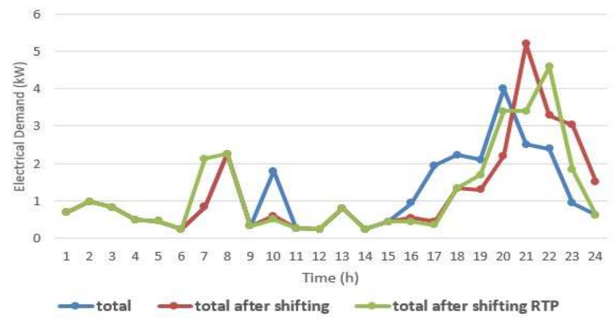

Figure 5. Electrical demand profile before and after load shifting

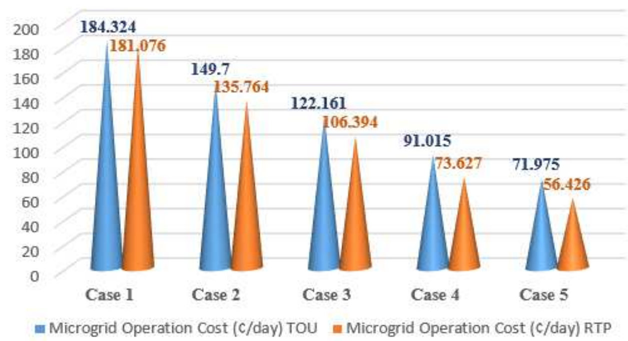

Figure 6. Microgrid operation cost in 5 cases in both TOU and RTP Tariffs

TABLE III. TOU AND RTP TARIFFS (€/KWH)

Hour(h)	TOU	RTP	Hour(h)	TOU	RTP
1	6.2	5.6	13	9.2	10.4
2	6.2	5.8	14	9.2	10.5
3	6.2	6	15	9.2	10.6
4	6.2	6.1	16	9.2	10.4
5	6.2	6.3	17	9.2	9.2
6	6.2	6.5	18	10.8	8.7
7	6.2	7	19	10.8	8.5
8	10.8	8.3	20	6.2	8.1
9	10.8	9.5	21	6.2	7
10	10.8	9.7	22	6.2	6
11	10.8	10	23	6.2	5.8
12	9.2	10.2	24	6.2	5.7

VI. CONCLUSION

In this paper a detailed modeling of CCHP unit for energy management in smart micro grid ,located in a region with hot weather, has been presented. The microgrid power sources are CCHP and PV units and battery of an electric car is used as energy storage. Heat and electric efficiency of the micro-CCHP unit are considered variable for a more real simulation. Electric, heat and cool loads are considered in simulations. Five cases are simulated and results showed that the cost of micro grid utilization has been reduced by smartening and controlling the micro grid step by step.

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