



# Flexibility Enhancement of Energy Delivery Systems through Smart Operation of Micro Energy Hub

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## Abstract

In this paper smart operation of micro energy hub is presented. Energy hub system consists of certain energy hubs and interconnectors that are coordinated by energy hub system operator. An energy hub contains several converters and storages to serve demanded services in most efficient manner from available energy carriers. In this paper, the flexibility of energy delivery point is enhanced using micro energy hub concept. Smart micro energy hub is operated in minimum cost considering the price of input energy carriers, the amount of forecasted output energy carriers and the available facilities included in the hub. Regarding this matter, two micro energy hubs with different characteristics are modelled which are equipped with CHP unit, warmer, boiler and heat storage. The effectiveness of the proposed system is validated by running numerical study on a test system.

**Keywords:** Energy delivery, flexibility enhancement, micro energy hub, multi-energy system.

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## Nomenclature

### Indices:

$i$	Index of a CHP unit
$j$	The electric bus of a generating unit.
$k$	Gas load point.
$t$	Time scale

### Parameters:

$HR$	Gas to electric energy transformation coefficient.
$H_i^{\max, storage}$	Maximum capacity of heat storage
$L_{i,t}^{e, customer}$	Electric demand of customer
$L_t^{e, forecast}$	Forecasted electric demand
$L_{i,t}^{g, customer}$	Gas demand of customer

$L_{i,t}^{h, customer}$	Heat demand of customer
$L_i^{\max, gas}$	Maximum amount of input gas to CHP
$L_i^{\max, chp}$	Maximum amount of output heat from CHP
$L_i^{\max, storage}$	Maximum amount of input/output rate of storage
$P_{O_{\max}}^{e, chp}$	Maximum generation of a CHP
$P_{O_{\min}}^{e, chp}$	Minimum generation of a CHP
$P_t^{e, dm}$	Day ahead market price
$P_t^{e, sm}$	Spot market price
$P_{k,t}^g$	Gas price
$R_i^{e, chp}$	Electrical efficiency of a CHP unit
$R_i^{h, boiler}$	Efficiency of boiler

$R_i^{h, chp}$	Thermal efficiency of a CHP unit
$R_i^{h, warmer}$	Efficiency of warmer
$Rr_i$	Ramp rate of a CHP unit
$T_i^{off}$	Minimum up time of a CHP unit (hour).
$T_i^{on}$	Minimum down time of a CHP unit (hour).
$\alpha_i$	Heat loss coefficient
<i>Variables:</i>	
$Cost^e$	Electricity cost
$Cost^g$	Gas cost
$h_{i,t}^{storage}$	Stored heat
$l_{i,t}^e$	Axillary variable
$l_{i,t}^{e, EHSO}$	Exchanged power with grid
$l_{i,t}^{e, warmer}$	Input electricity to the warmer
$l_{i,t}^{exhust, chp}$	Exhausted heat from CHP unit
$l_{i,t}^{in, storage}$	Input heat to the heat storage
$l_{k,t}^g$	Customer gas consumption
$l_{i,t}^{g, boiler}$	Input gas to the boiler
$l_{i,t}^{g, chp}$	Input gas to the CHP
$l_{i,t}^{g, EHSO}$	Input gas to energy hub from grid
$l_{i,t}^{h, boiler}$	Output heat of boiler
$l_{i,t}^{h, warmer}$	Output heat of warmer
$l_{i,t}^{loss, storage}$	Heat loss of storage
$l_{i,t}^{out, chp}$	Output heat of CHP
$l_{i,t}^{sys}$	Injected heat to heat storage and load
$PO_{i,t}^{e, chp}$	Output power of CHP
$I_{a_{i,t}}$	Decision variable (1 if unit is available, otherwise zero).

## 1. Introduction

Nowadays, energy plays a vital role in sustainable development of societies. One of the main aspects of sustainable energy system is enhancement of energy system flexibility to confront economical and technical issues as well as utilizing appropriate energy carriers [1]. Fundamentals of sustainable energy systems are Distributed Energy Resources (DERs) and efficient energy

system[2]. DERs include energy converters (e.g. DG and CHP technologies), storages and Demand Side Management (DSM) Programs. Storages and DSM programs improve time based flexibility through load shifting. On the contrary to this time based flexibility, energy converters can substitute the demand of one energy carrier to other ones. These characteristics inherently exist in smart multi-energy systems.

The energy hub system is a mathematical model for modelling the integrated multi-energy systems, which are composed of a certain number of energy hubs and energy interconnections [2]. A hub is the center of operation on which the input energy carriers are converted to output energy services or required energy forms. The interconnections are the corridors that exchange energy carriers between energy hubs [3]. Smartness of energy hub system facilitates interactions between system elements and enhances system flexibility. Each hub can operate its authorized area from economical and technical aspects.

In this paper, an operational framework for micro energy hubs is introduced which enhance the flexibility of energy delivery points. Moreover, the impact of energy hub components efficiency in system flexibility is investigated. The considered micro energy hub consists of CHP unit, warmer, boiler and heat storage. These devices are controlled by a centralized operator to deliver the forecasted electricity, heat and natural gas demand. The energy hub operator runs an optimization problem to determine the optimum operation of the mentioned devices minimizing the total cost of the system. Regarding this matter two energy hubs are considered with different characteristics to emphasize the importance of component's efficiency on optimum solution. Moreover, two scenarios are assumed to represent the practical constraints of different electricity markets; namely unidirectional and bidirectional power flow with the grid. Finally, a comprehensive discussion is conducted on the numerical results and the practical points are extracted.

The remaining of the paper is organized as follows. In Section 2, the smart micro energy hub characteristics are discussed. In Section 3, the control framework of micro energy hub is modelled. Numerical results are demonstrated in Section 4. Concluding remarks are provided in Section 5.

## 2. Smart Micro Energy Hub

The energy hub system is a mathematical model developed for modeling the behavior of integrated multi-energy systems. The physical demonstration of energy hubs are the integration of compact energy

converters, storages and control facilities which deliver required services from input energy carriers. Fig.1 shows a typical micro energy hub which consists of transformer, CHP, boiler, furnace, heat storage and chiller.

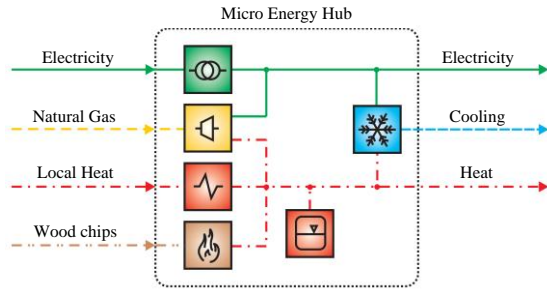


Fig.1. A typical micro energy hub

Firstly, this concept of micro energy hub was introduced in ref [3]. Ref [4-6] investigated the modeling of energy hub systems elements including energy hubs and interconnectors. Moreover, the whole energy hub system was modeled in ref [7-10] optimal energy flow to determine operation plan of the system was addressed.

The size of hubs can vary from small scale applications such as a smart home (Micro hubs) to extensive areas, e.g. a province or even a country (Macro hubs)[11, 12]. The differences between these two groups is not only based on their size but also related to their performance. Micro hubs are mostly small hubs with tendency to centralized control and cooperation with their neighbor hubs. In future smart energy networks, these hubs will play an important role as small construction blocks of macro energy hubs.

Flexibility and freedom in decision making are the main motivation of multi energy systems. Increasing inherent system flexibility will be possible by developing multi-energy systems and energy converter technologies. Inherent system flexibility will be enabled by improving system smartness. Smartness in micro energy hubs enables real time decision making by comparing price signals and service consumption.

### 3. Control Framework

As it was mentioned before, the concept of energy hub in smaller scales can be defined as residential consumers and in more large scales may be defined as regional or whole country consumptions. In both of aforementioned definitions, this concept will have special objectives and constraints while following different studying procedure. For example, in small scales, issues concerning optimal operation of energy hub have more importance while in large scales strategic

planning and its cooperation with each other from various points of view such as stability, economic, political and social visions in long-term have a lot more importance.

In this paper, small scale energy hubs with residential, commercial, official and public usages are considered and are referred to as “micro energy hub”. Fig.2 depicts the components of micro energy hub which consists of entrance and exit terminals of energy carriers, energy converters and storages, and communicational and control infrastructure. As it can be observed in the picture, each of the micro-hubs is controlled by operator of energy hub system. This entity has the responsibility of managing and delivering the energy demand for all consumers as well as providing the cooperation between all micro energy hubs. In the following, the proposed modeling for functional framework of micro energy hub system operator will be described.

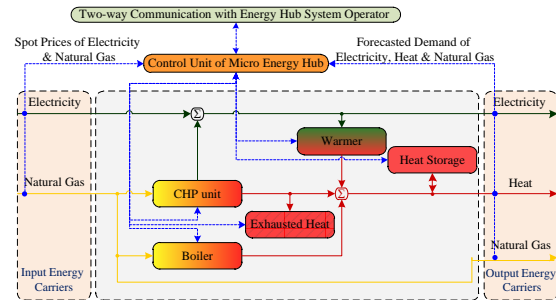


Fig.2. The proposed operational diagram of smart micro energy hub

#### 3.1. Objective function

In the proposed model, the objective of energy hub operator is to reduce the expected total energy cost for each consumer. This entity tries to make use of micro energy hubs' facilities and forecast spot market price for whole day in order to prepare the choice between two energy carriers i.e. the electricity and gas; therefore, the objective function can be stated as equation (1) in the form of minimizing the total operational costs of electricity and gas energy carriers:

$$\text{Min } Cost^e + Cost^g \quad (1)$$

The operator of energy hub system will forecast the consumers demand, based on which will buy the required amount of electricity from day-ahead market. In the day of operation, this entity can minimize the operation cost of energy hub system by taking into account the amount of consumer demand forecasting error, real-time electricity price, and existing facilities in micro energy hub.

$$\begin{aligned}
Cost^e = & \sum_t L_t^{e,forecast} * P_t^{e,dm} \\
& + \sum_t \left( \left( \sum_j L_{j,t}^e \right. \right. \\
& \left. \left. - L_t^{e,forecast} \right) \right. \\
& \left. - \sum_i PO_{i,t}^{e,chp} - l_{i,t}^{e,warm\ err} \right) \\
& * P_t^{e,sm}
\end{aligned} \quad (2)$$

On the other hand, the gas fuel price is considered to be constant therefore the gas fuel cost can be calculated from equations (4):

$$Cost^g = \sum_t \sum_k l_{k,t}^g * P_t^g \quad (4)$$

$$if \quad k \in i \text{ chp nodes} \Rightarrow l_{k,t}^g = l_{i,t}^{g,EHSO} \quad (5)$$

### 3.2. Constraints

**Entering energy carriers:** as it can be seen in Fig.2, the gas entering into the system is divided into three parts: gas entering into combined heat & power unit, gas needed for consumers, and gas entering into boiler (equation (6)). Moreover, the electrical power entering into the system also can be divided into the part used for warmer and the other part providing the consumer required electricity (equation (7)).

$$l_{i,t}^{g,EHSO} = l_{i,t}^{g,chp} + L_{i,t}^{g,customer} + l_{i,t}^{g,boiler} \quad (6)$$

$$l_{i,t}^{e,EHSO} = l_{i,t}^e + l_{i,t}^{e,warm} \quad (7)$$

$$0 \leq l_{i,t}^{g,chp} \leq L_i^{max,gas} \quad (8)$$

**Combined heat and power unit:** this unit has the ability to produce heat and electrical power simultaneously where the amount of each product is related to the electrical and heat efficiency of the unit as well as the amount of its consumed fuel (equations (9) & (10)). Taking into mind that all CHP units are operated in most economical condition, like when maximum production of electrical power is economical but the amount of heat produced is more than needed, then the residual heat can be stored in heat storages according to equation (11) or the rest will be wasted.

$$l_{i,t}^{out,chp} = R_i^{h,chp} * l_{i,t}^{g,chp} \quad (9)$$

$$PO_{i,t}^{e,chp} \leq R_i^{e,chp} * HR * l_{i,t}^{g,chp} \quad (10)$$

$$l_{i,t}^{out,chp} = l_{i,t}^{sys} + l_{i,t}^{exhaust,chp} \quad (11)$$

$$0 \leq l_{i,t}^{out,chp} \leq L_i^{max,chp} \quad (12)$$

Moreover, electricity generator of CHP unit has some operational constraints such as minimum and maximum output power, ramp up rate limit, and minimum up and down time which are stated through equations (13) to (17):

$$PO_{min}^{e,chp} * I_{a_{i,t}} \leq PO_{i,t}^{e,chp} \leq PO_{max}^{e,chp} * I_{a_{i,t}} \quad (13)$$

$$PO_{i,t-1}^{e,chp} - PO_{i,t}^{e,chp} \leq Rr_i \quad (14)$$

$$PO_{i,t}^{e,chp} - PO_{i,t-1}^{e,chp} \leq Rr_i \quad (15)$$

$$T_i^{off} * (I_{a_{i,t}} - I_{a_{i,t+1}}) + \sum_{h=t+2}^{t+T_i^{off}} I_{a_{i,h}} \leq T_i^{off} \quad (16)$$

$$T_i^{on} * (I_{a_{i,t+1}} - I_{a_{i,t}}) + \sum_{h=t+2}^{t+T_i^{on}} (1 - I_{a_{i,h}}) \leq T_i^{on} \quad (17)$$

**Heat storage:** thermal power gained from heat producer units (CHP, electrical, and boiler) directly provide heat demand while the rest will be stored in the heat storage. Storing thermal energy will smooth the consumers' heat demand and gives the opportunity of optimal operation. It worth mentioning that, due to more simple technologies of these storages comparing to electricity storages they will cause far less installation costs. The amount of stored heat in these storages depends on the amount of its input our output thermal power, the amount of thermal loss, and their stored heat in former time interval (eq. (18)). On the other hand, they have limited increase and decrease rate of thermal power (eq. (20), (21)). The heat storage loss amount is also related to the amount of existing heat in the storage with a constant factor (eq. (22)).

$$\begin{aligned}
h_{i,t}^{storage} = & l_{i,t}^{in,storage} - l_{i,t}^{out,storage} - \\
& l_{i,t}^{loss,storage} + h_{i,t-1}^{storage}
\end{aligned} \quad (18)$$

$$0 \leq h_{i,t}^{storage} \leq H_i^{max,storage} \quad (19)$$

$$0 \leq l_{i,t}^{in,storage} \leq L_i^{max,storage} \quad (20)$$

$$0 \leq l_{i,t}^{out,storage} \leq L_i^{max,storage} \quad (21)$$

$$l_{i,t}^{loss,storage} = \alpha_i * h_{i,t}^{storage} \quad (22)$$

**Warmer:** producing combined heat and electrical power along with reducing the overall energy consumption resulting from higher system efficiency, will represent a rightful choice between consuming electricity from electrical grid or supplying it through CHP units. By adding one electrical warmer to the system, the choice between electricity and gas carriers will be made. This intrigue is highly efficient especially during midnights or first hours of cold days where the consumption and price of electricity are considerably low while on the other hand, consumption of gas energy will experience its peak. In this situation, low price electricity can be stored in heat form and being used in another appropriate time. The amount of heat produced from warmer is related to its thermal efficiency according to equation (23):

$$l_{i,t}^{h,warmerr} = R_i^{h,warmerr} * l_{i,t}^{e,warmerr} \quad (23)$$

**Boiler:** due to economical design and operation of CHP units, it is not possible to fully cover the thermal demand from the output heat of CHP unit; as a result, boilers are used to provide consumers with the required thermal power. Moreover, the presence of boilers during maintenance of CHP units is requisite. It has to be stated that the heat amount produced from these heaters depends on their thermal efficiency (eq. (24)).

$$l_{i,t}^{h,boiler} = R_i^{h,boiler} * l_{i,t}^{g,boiler} \quad (24)$$

**Output energy carriers:** The final output of micro energy hub can completely provide the electricity and heat requirements of the consumer. Electric power is the total sum of output power of CHP units and power from electrical grid excluding the power consumed by the warmer (eq. (25)). In addition, thermal power is the total summation of power gained from CHP units, gas and warmer and net injected power into the heat storages (eq. (26)).

$$L_{i,t}^{e,customer} = l_{i,t}^{e,EHSO} + pO_{i,t}^{e,chp} - l_{i,t}^{e,warmerr} \quad (25)$$

$$L_{i,t}^{h,customer} = l_{i,t}^{sys} + l_{i,t}^{h,warmerr} + l_{i,t}^{h,boiler} + l_{i,t}^{out,storage} - l_{i,t}^{in,storage} \quad (26)$$

#### 4. Numerical Study

Fig. 3 and 4 depicts heat and electricity demand diagrams for two residential household consumers during 24 hours of a day in PJM power market respectively. Electric and thermal power of these two consumers is provided from their own micro energy hub and is controlled by energy hub system operator.

Fig.5 depicts the actual and forecasted demand for whole consumers within energy hub area. As it is shown, the actual demand differs from the forecasted amount which necessitates optimal employment of existing facilities available for energy hub system operator in order to cover demands in a least cost manner. The characteristics of CHP units are explained in Table.1. Fig.6 shows the day-ahead and real-time price of electricity for a typical energy hub operator in PJM.

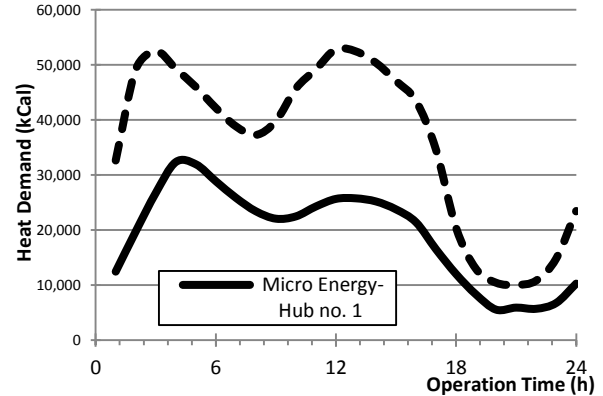


Fig.3. Thermal demand in micro energy hubs (1) and (2)

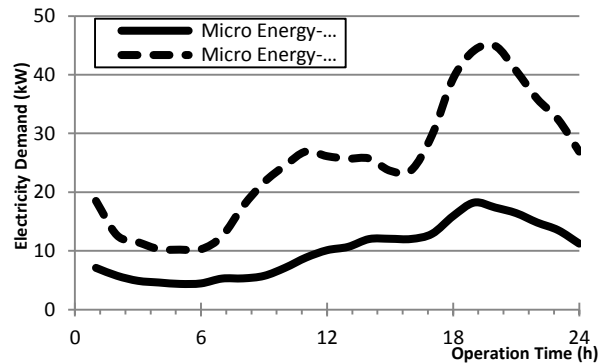


Fig.4. Electrical demand in micro energy hubs (1) and (2)

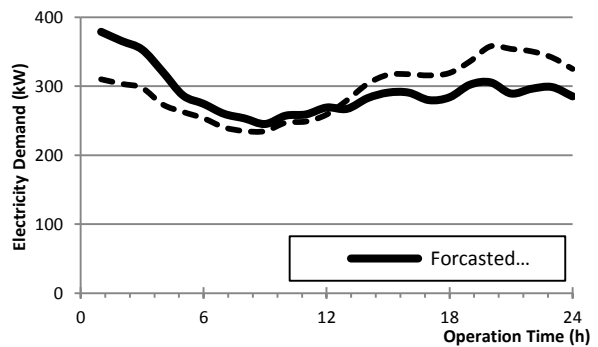


Fig.5. Actual and forecasted electricity demand for whole consumers in energy hub system area

Numerical results are calculated for two scenarios:

- Micro energy hub can only receive electricity from grid and cannot inject electricity into the grid.
- Micro energy hub has bidirectional relation with the grid and can sell the surplus electricity to grid.

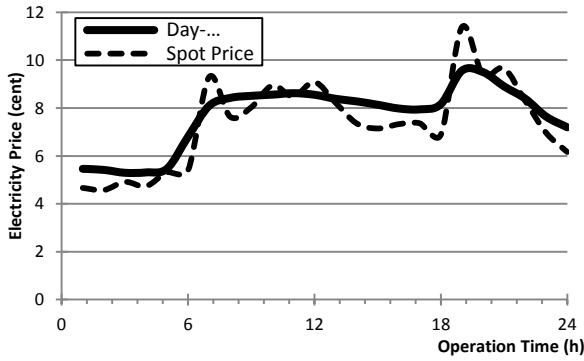


Fig.6. Day-ahead and real-time electricity price in energy hub system

**Second period (hours 5-12):** in this period, the electricity price is rather high and generating electricity with CHP unit is appropriate; therefore, CHP unit is operating according to electricity demand and heat shortage is covered by boiler that has high thermal efficiency. It is observed, that all of the heat from heat storage is used in this period; as a result, in this period, only gas energy carrier is used for producing output energy carriers

**Third period (hours 13-16):** in this period, both electricity and heat are more than the maximum electricity and heat requirement of CHP unit; therefore, it is beneficial to turn on the CHP unit and operate with its nominal capacity. Obviously, shortage of electricity and heat has to be provided with lowest cost. Consequently, the boiler will provide the required heat while electricity shortage is supplied from the grid. As a result, in this period, gas energy carriers have more share in initial energy carriers.

Tabel.1  
Micro energy hub components characteristics

Micro Energy Hub no.	CHP Unit				Warmer	Boiler		Heat Storage
	$P_{min}$ (kW)	$P_{max}$ (kW)	Electrical Efficiency (%)	Thermal Efficiency (%)	Efficiency (%)	Efficiency (%)	Capacity (kCal)	Heat loss Coefficient (%)
(1)	0	11	23	54	90	70	16821	5
(2)	0	22	30	45	90	75	47167	5

Fig.7 and 8 illustrate the usage of heat and electricity energy resources existing in first micro-hub for supplying the heat and electricity demand of consumer (1) respectively. As it is shown, operation of micro energy hub can be divided into four time periods:

**First period (hours 1-4):** In this period the electricity price is low; therefore, the required heat is provided from warmer. For instance, in hour 2, the generated heat is more than the demand, hence is stored in heat storage, and then it is used in hour 3. On the other hand, during these hours, purchasing electricity from the grid is also beneficial; therefore, electric energy carrier has the highest share in output energy carriers' and supplies in this period.

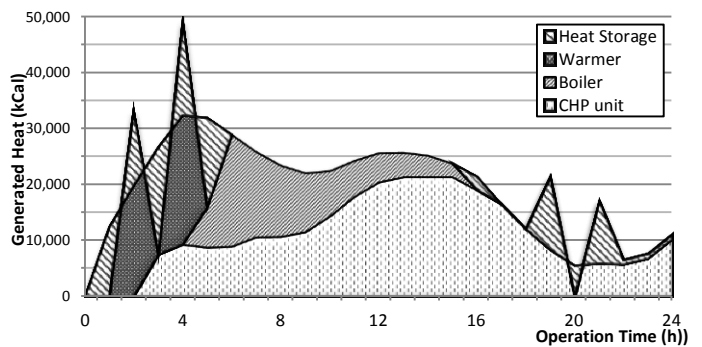


Fig.7. Heat supply of micro energy hub (1) in first scenario 1

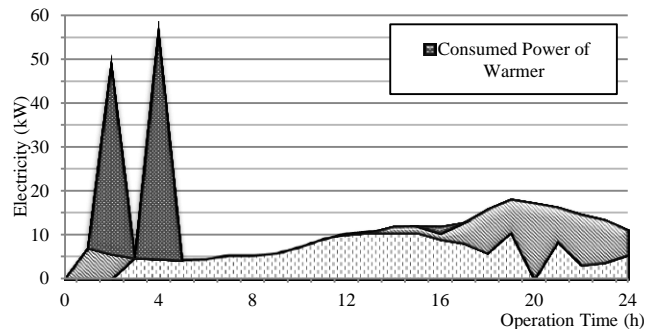


Fig.8. Electricity supply of micro energy hub (1) in first scenario 1

**Fourth period (17-24):** in this period, the heat demand will reduce while the electricity price increases dramatically. Therefore, CHP unit operates based on heat to efficiently manipulate all facilities of CHP. However, as it can be seen in Fig.7 and 8, in hours 19 and 20 the generated heat from CHP is more than consumers' requirements and is stored in heat storage. This is due to high real-time electricity price during these hours which makes it beneficial for CHP unit to generate more heat in order to reduce the purchased electricity from the grid and consequently minimize the overall system cost. By comparing CHP units with electric and boiler in both micro energy hubs number (1) and (2), the followings are resulted:

- Higher electrical efficiency of CHP in micro energy hub number (2) rather than micro-hub number (1)
- Higher thermal efficiency of CHP in micro energy hub number (2) rather than micro-hub number (1)
- lower efficiency of boiler in micro energy hub number (2) rather than micro-hub number (1)
- same efficiency of warmer in both micro-hubs

Fig.9 and 10 depicts the micro energy hub operation for consumer (2). Comparison of this Fig. with Fig.7 and 8 will result in:

- More share and impact of boiler in providing output heat which is considerable during first hours of a day;
- More usage of electricity generated by CHP units especially during expensive electricity hours, and storing the surplus heat in hours 19 to 21 in heat storage;
- To sum up, it can be stated that unlike CHP unit (1) that operates mainly on thermal factors, CHP unit (2) operates mainly based on electrical factors;

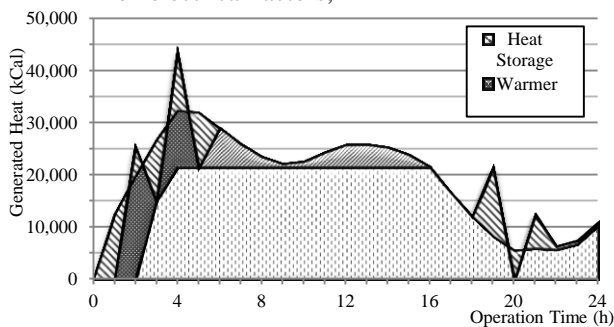


Fig.9. Heat supply of micro energy hub (2) in first scenario 1

Fig.11 and 12 show the operational procedure of micro energy hub (2) in a way that the residual electricity can be sold to the grid. By comparing these Figures with Fig.9 and 10 these results are achieved:

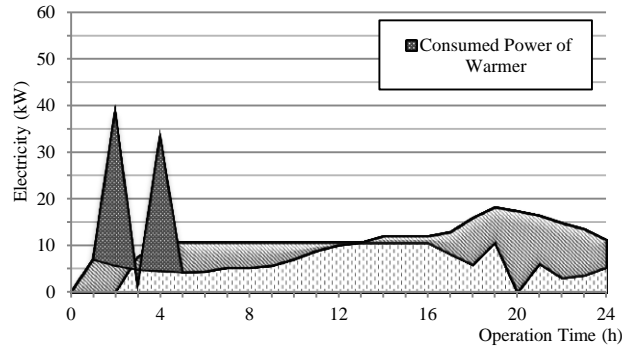


Fig.10. Electricity supply of micro energy hub (2) in first scenario1

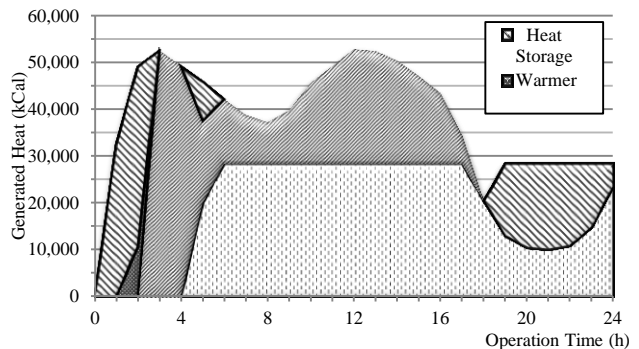


Fig.11. Heat supply of micro energy hub (2) in first scenario 2

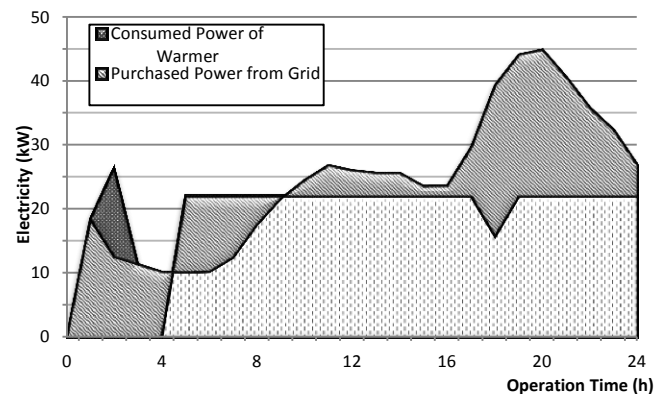


Fig.12. Electricity supply of micro energy hub (2) in first scenario2

- In this condition, CHP unit operates with nominal capacity during high price electricity hours. In hours 5 to 9 the residual electricity is sold to the grid while during hours 21 to 23 less electricity is purchased from the grid

- Since in expensive electricity hours, the heat generated in CHP unit is more than the required amount, therefore, more heat will be stored in heat storage. As a result, the need to use warmer will reduce;
- In an overall state, usage of existing facilities has been more efficient and comparing to previous condition, the cost of energy system operation has decreased.

## 5. Conclusion

In this paper, the operation problem of micro energy hub is investigated and smart operational framework is introduced to enhance the flexibility of energy delivery point. Deployment of the proposed framework has leads to minimum operation cost of micro energy hub by optimum utilization of its available facilities. It was shown that, increasing the smart technologies and communication infrastructure may increase the flexibility of energy delivery point through optimum operation of existing assets. Increasing the penetration of micro energy hubs in future energy systems and their cooperative coordination shall increase the security of energy supply chain significantly. Moreover, by increasing the flexibility in choosing between different energy carriers the customer dependency to specific energy carrier is mitigated and the reliability of customer's energy delivery will be enhanced.

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