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Article

Optimal Operation of a Village Energy System Considering Renewable Resources and Battery Energy Storage

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Abstract: In this paper, a village energy system is coupled with the wide-area energy network based on the energy hub concept. The village is modeled as an isolated energy hub while it could interact with the energy sub-networks including the electrical, and natural gas through the market. The energy demand of village is supplied with renewable resources such as photovoltaic (PV) system and other generation such as combined heat and power (CHP) technologies. The CHP unit is modeled by the part-load performance. In addition, the battery energy storage is presented beside the PV system to damp the intermittent generation of PV and to be utilized in the high prices of the market. The optimal operation problem is solved to maximize the profit from the energy hub operator point of view. The optimization problem is solved with the teaching-learning based optimization (TLBO) method. The results show that the proper interaction of the village energy system with the upstream sub-networks is so affordable for the system operator to increase the profit, in a way that the maximum benefit of village energy system is reached to 3.6456$.

Keywords**:** energy hub, energy systems, electrical storage, PV, CHP

1. Introduction

The confident and reliable supplying of energy is a crucial issue for system operators. There are different resources of energy with various capacities and prices that make the system operators to manage their energy consumptions. The resources of fossil fuels are going to the end and therefore the prices of these type of energy carriers are increased. Besides, the renewable energy resources with low prices have become so popular in supplying the required energy of the systems. However, the intermittent nature of the renewable generations will make the system operators balance the energy consumption and production with the new energy storage technologies. The combination of renewable energy generation and energy storage systems is a very promising method and they are becoming an essential component of energy supply and demand matching [1,2]. The energy systems are defined as the combination of sub-networks in which different type of energy networks such as the electrical and natural gas can interact and connect to each other through the energy carriers. The optimal interaction of energy carriers could happen in various levels such as country, city, region, or within a district [3]. This issue shows an important possibility to increase the optimal operation of integrated energy networks and this integrated view opens a new window on the research of synergies [4]. The modeling, formulation and optimal operation of integrated energy networks are investigated in many kinds of research as in [5–10]. Most of these researches are accomplished with the purpose of reduction in the operation cost as well.

Over the last years, the concept of "energy hub" has become a key approach in the vision of future energy network [11]. An energy hub is identified as a unit where multiple energy carriers can be produced, converted,

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stored or consumed and it includes three main components: (i) energy resources, (ii) energy converters and storages, and (iii) energy demands. The idea of energy hub is a very promising option that can be applied to a wide variety of integrated energy systems [12]. Some different concepts and models which are utilized in the literature for energy hub is reviewed completely in [13]. In addition, the optimal planning, scheduling and operation of energy hub systems are investigated by some researches in [14–16] while the authors in [17–19] analyzed the optimal operational problem of integrated energy systems with the concept of energy hub as a new approach. The real facilities that can be modeled through the concept of energy hub are industrial plants, huge building complexes, small isolated networks, rural and urban domains. [20]. In the mentioned researches, the optimal operational problems of energy systems are accomplished in various scales such as distribution [18,21], urban [17,22], smart district [7], community [19], residential [23] and home [24,25].

The energy hub systems have the particular advantage of providing flexibility to cope with the impacts of the penetration of renewable energy sources [15]. The results of [15,21] suggested that a grid-integrated energy hub consisting of the PV system and wind turbines can supply a high percentage of the annual energy demand and therefore the authors in [23,24] have been inserted the renewable power resources to their energy system. Due to the unpredictable features of renewable energy resources, some researches advised the utilization of energy storage systems besides the renewables. As a result, the authors in [23,26] proposed the energy storage systems for the day-ahead scheduling of energy networks. The interaction power between the energy system components are rarely happened through the markets. The authors in [27] proposed a pricing power market for their networks, but this issue is not considered in the sub-network and energy hub integration.

2. Energy System Description

In this paper, a village energy system is modeled as an isolated energy hub which is connected to the large-scale upstream sub-networks. Dependent on the scale of the energy systems, they could separate into various types of wide-area and local-area systems. In this context, the large-scale connected upstream sub-networks are called the wide-area energy systems and the isolated energy hub of village is named the local-area system. The wide-area energy systems consist of the electrical and natural gas energy sub-networks. In the local-area energy system, a solar PV and other generation units as the CHPs are utilized. Moreover, an electrical energy storage is included in the energy hub to reduce the insufficient generation capacity by the PV and smooth its generation fluctuation. The optimal scheduling of electrical storage is also investigated. The CHP unit in the local-area energy system receive its required natural gas from the wide-area network and supply the village energy hub power and heat demands. In fact, the CHP has an impressive role in supplying the power and heat of local-area network and it is modeled as part-load performance.

The main novelty of this manuscript is to set up an economical interaction between the large-scale and local-scale networks through the energy market size so that we reach to the maximum profit from the operator view point of village energy system. Since the presence of renewable and storages as the ancillary energy resources beside CHPs could have many side effects in the market energy size, the role of these resources in the village energy system are also investigated as well. The energy resources are scheduled to supply the load requirements of the village energy hub with minimum cost. In doing so, the costs can be effectively minimized by the interactions of the energy hub and wide-area sub-networks through the market. Actually, from the viewpoint of the system operator, the proper interactions of village energy hub with the wide-area energy networks at low and high market prices can lead to a maximum profit. In summary, the village energy hub interacts with the wide-area sub-networks in three modes: 1- Receive the shortage energy from the wide-area network during low-cost hours, 2- Send the surplus energy to the wide-area network during high-cost hours for maximizing the profit, and 3- Being standby and store the surplus generated power. The wide-area and local-area energy systems integration are accomplished through the market. The technical difficulties in obtaining the results are the electrical energy resources such as PV and energy storage, inserting the CHP model in the energy hub systems, and supplying the demand of connected load with the minimum operational cost. Furthermore, the optimal operation problem of village energy hub is solved using the TLBO algorithm as well.

3. Energy System Formulation

In the following subsections the general structure of studied energy system, the modeling and formulation of energy hub and its components, the utilized electricity market, the formulation of optimal optimization problem and utilized TLBO algorithm are expressed as well.

3.1 *Energy System Structure*

As mentioned before, the energy systems are the combination of some sub-systems in which they could interact with each other. In this context the studied energy system and the connections of wide-area and local-area energy networks are illustrated in Figure 1. As shown in Figure 1, a village is considered as an energy hub. The energy hub consists of energy converters like CHP that consume natural gas and provide power for the output demands. The required gas of CHP is supplied by the natural gas wide-area energy system. The main loads of this village energy hub are supplied with the CHP technologies and PV systems as the renewable energy resources. Besides the electrical sub-network as the other wide-area energy system would contributes in the process of supplying the demanded power of energy hub through the energy market. Moreover, a battery as an electrical energy storage system is also presented in the village energy hub to smooth the intermittent generation of the PV and to store the surplus generated power during the standby situations.

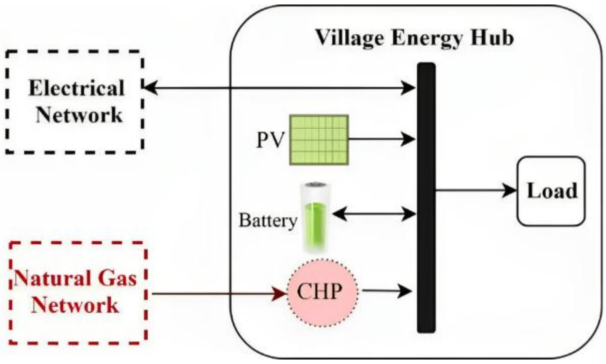

Figure 1. The wide-area and local-area energy systems connections.

3.2 *Energy System Modeling*

The model of village energy hub network that is illustrated in Figure 1, consists of some generation components as an input and the load as an output. The load of village energy hub are combinations of electrical and heat power demands. Also, it has a battery that stores excess input energy and discharge it during peak hours. The output and input energy equations of the mentioned village could be expressed as (1).

$$P^{G} = P^{load} - P^{CHP} - P^{PV} \pm P^{battery} \tag{1}$$

In (1), P^G is the injected power from the wide-area electrical sub-network, P^{CHP} is the generated power by the CHP technology, P^{PV} is the produced power by the PV system and $P^{battery}$ is the exchanged power between the battery storage and the energy hub.

The CHP unit is modeled by the part-load performance in this paper. It is assumed that the generation of CHP heat power and its temperature are known. Therefore, by assuming these points, the generated electrical power of CHP unit could be expressed as (2) and (3).

$$P_{E,i}^{chp} = \begin{cases} a_i^{chp}\phi_i^{chp} + b_i^{chp}T_{s,i}^{chp} + c_i^{chp} & r_{1,i}\phi_i^{chp,\max} \le \phi_i^{chp} \le \phi_i^{chp,\min} \\ a_i^{chp}\phi_i^{chp} + b_i^{chp}T_{s,i}^{chp} + c_i^{chp} - w_{1,i} & r_{2,i}\phi_i^{chp,\max} \le \phi_i^{chp} \le r_{1,i}\phi_i^{chp,\min} \\ a_i^{chp}\phi_i^{chp} + b_i^{chp}T_{s,i}^{chp} + c_i^{chp} - w_{1,i} - w_{2,i} & \phi_i^{chp,\max} \le \phi_i^{chp} \le r_{2,i}\phi_i^{chp,\min} \end{cases} \tag{2}$$

$$w_{1,i} = \left(r_{1,i}\phi_i^{chp,\max} - \phi_i^{chp} \right)\mu_{1,i} \tag{3a}$$

$$w_{2,i} = \left(r_{2,i}\phi_i^{chp,\max} - \phi_i^{chp} \right)\mu_{2,i} \tag{3b}$$

Equation (2) states the CHP's part-load performance and'a_i', 'b_i', 'c_i', are the constant coefficients of the CHP as well. In (3), the generated power which is resulted by the part-load operation is defined by the positive coefficients of μ_1 and μ_2. Besides, the power generation changes are limited by r_1 and r_2. In addition, the total constant efficiency under part-load situations is taken into account. Therefore, the injected gas flow of the i_{th} CHP can be calculated by (4).

$$f_i^{chp} = \frac{P_{E,i}^{chp} + \phi_i^{chp}}{\eta_i^{chp}} \tag{4}$$

where η_i^{chp} is the CHP's general efficiency. To obtain the demanded gas from the wide-area network in standard cubic meter (SCM), the output of equation (4) should be multiplied to 3.14/40.611 [28].

The technical and economic performance features of battery energy storage must be taken into account to reach the optimum operation of total energy network. The formulations of the battery storage model are as (5)–(9) [2,29].

$$E_{e,\min} < E_e(t) < E_{e,\max} \quad \forall t \tag{5}$$

$$E(t+1) = E(t) + P_c(t) \cdot \Delta t \cdot \eta_c^e - P_d(t) \cdot \Delta t \cdot 1/\eta_d^e \tag{6}$$

$$0 < P_c(t) < P_{c,\max} \tag{7}$$

$$0 < P_d(t) < P_{d,\max} \tag{8}$$

$$P_c(t) \cdot P_d(t) = 0 \quad \forall t \tag{9}$$

The state of charge (SOC) battery at each time period is described as $E_e(t)$. The border of SOC is bounded by (5) and it should be updated at each time period in (6). In (6), η_d^e and η_c^e are the discharging and charging efficiency and they are limited between 1 and 0. This limit state that a part of power should be discharged or stored in the battery. The discharging and charging efficiency are set to 0.9. Also, the maximum and minimum capacity of battery are 25 and 0 kWh, respectively. Moreover, the charging and discharging rate of battery is stated as $P_c(t)$ and $P_d(t)$, while the upper and lower limits of them should be satisfied in (7) and (8). The maximum rate of charging and discharging of battery are stated as $P_{c,\max}$ and $P_{d,\max}$, respectively. In (9) it is supposed that the battery can only charge or discharge at each time period as well. The primary amount of $E(t=0)$ is equal to E_0. Also, the final amount of $E(t)$ is equal to the primary amount E_0. If $\Delta E(t)=E(t+1)-E(t)$ is determined as the diversity of SOC in two continuous period of time, it should be lower than $P_{d,\max}$ or $P_{c,\max}$.

3.3 *Electricity Market*

The electricity market is usually utilized in order to realize the economic costs and benefits procedure. In other words, the various tariff of electricity in different time of the day would control the behavior of loads consumption and resources production. In this paper, it is assumed that the electricity market has three values in the time intervals of peak, intermediate and off-peak.

The values of electricity market are shown in Figure 2 for each time interval. It should be mentioned that the effects of the market are considered in the optimal operation costs of the village energy hub as well.

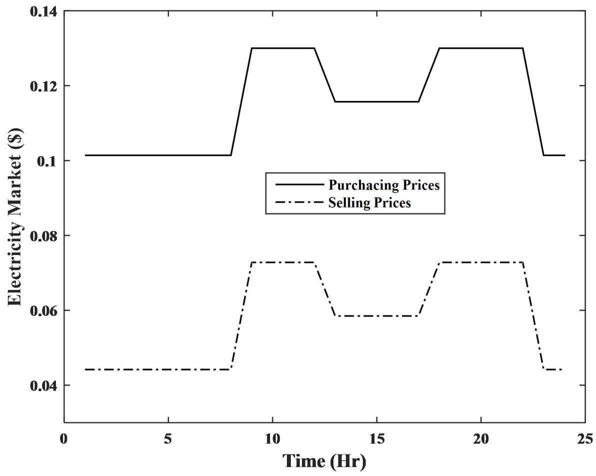

Figure 2. The electricity market values.

3.4 *Objective Function*

In the multi-period optimization, multiple time intervals of the systems should be considered. The optimization problem in the continuous conditions for the energy hub can be stated as follows:

$$
\begin{aligned}
&\text{Minimize } F^{hub}(x,t) \quad t \in \{1,2,3,\cdots,N_t\} \\
&\text{Subject to} \\
&g^{hub}(x,t) = 0 \quad \forall t \\
&h^{hub}(x,t) < 0 \quad \forall t
\end{aligned} \tag{10}
$$

where x is the state variables and $g^{hub}(x,t)$, $h^{hub}(x,t)$ are the equality and inequality constraints of the energy hub at each time interval. $F^{hub}(x,t)$ is the total cost of local-area energy system. In this village energy hub model the generation station of local-area energy system consume natural gas or they are renewables like PV and battery storage. The total cost of local-area energy system can be described by the following function as (11).

$$
F^{hub}(x,t) = \sum_{t=1}^{24}\left(C_{grid} + C_{gas}\right) \tag{11}
$$

In Eq. (11), C_{grid} is the cost function of wide-area electrical network, and C_{gas} is the cost function of purchasing from the wide-area natural gas network. The mentioned cost functions of energy systems are as the following (12) and (13).

$$
C_{grid} = T \times C^{g} \times P^{G} \tag{12}
$$

$$
C_{gas} = T \times C^{gas} \times f^{gas} \tag{13}
$$

3.5 *Solution Methodology*

The TLBO algorithm which introduced by Rao and colleagues is a metaheuristic technique. It works on the impression of a teacher on learners [30]. TLBO does not need specific parameters unlike other techniques and only needs a few control parameters for its operation. Due to the fact that TLBO algorithm does not have any setting parameters and also update the fitness function twice in each iteration of optimum process, it executes better than other algorithms.

4. Simulation and Results

The work of this paper has identified a proper modelling technique for evaluation of a GIS simplified model transient response due to a certain fault condition. It has proven that a simplified model emphasizes the focus on the fundamental aspects of the system and physical phenomenon without unnecessary complexities. Also, by establishing an accurate modelling procedure for the simplified model, the work has led to a better understanding of the underlying principles, enabling the development a solid foundation of knowledge. Strictly from a modelling perspective, understanding the applicability and limitations of the simplified model has provided insights into the conditions under which it is valid.

The optimal scheduling of wide-area and local-area energy systems are accomplished by implementing the TLBO algorithm. The presence of renewable PV system and battery storage beside the main energy supply resources (CHP and wide-area electrical network) are considered as well. Furthermore, the electricity market as shown in Figure 2 is implemented to reach the proper scheduling among different sources. The main purpose of the energy system is reaching to the maximum profit from the system operator point of view. The parameters of studied energy system are given in Table 1. As it is can be seen in this table, the time step of the optimal scheduling problem is set to one hour. Also, it is assumed that the PV system has the capacity of 50 kW and the battery storage SOC is equal to 5 kWh at the initial time. The other main parameters of the battery such as the charging and discharging rate, efficiency and the maximum and minimum capacity of the battery are stated in Table 1 as well. In addition, the cost of purchasing electricity from the wide-area electrical sub-network is according to Figure 2 while this value is set to 0.05 ($/kW) for purchasing gas from the wide-area natural gas sub-network. These values are constant in the energy market during each period of the optimal scheduling problem.

Table 1. Parameters of energy system

Length of time interval, T, (hr)	1
Initial energy in battery, (kWh)	5
Charging efficiency of battery	0.9
Discharging efficiency of battery	0.9
Maximum energy in battery, (kWh)	25
Minimum energy in battery, (kWh)	0
Cost of purchasing natural gas, ($/kW)	0.05

The results of optimization procedure are shown in Figure 3. In this figure, the battery storage charging and discharging values and also the purchasing and selling amount of power to the wide-area is illustrated with the positive and negative values. As it can be seen in the power values in Figure 3, during the times of 9 to 18 while the loads of village energy hub are low and the amount of generated power by the PV system is high enough, the energy system decided to sell some power to the wide-area electrical sub-network. On the other hand, during the night hours of the day (e.g. times of 19 to 22), due to the increasing in the consumption of local-area energy hub, the battery storage discharged and supplied the required power of the village as much as possible. Moreover, in these times the system operator decided to buy the shortage power from the wide-area electrical sub-network. The amount of purchased power form the electrical sub-network is equal to the difference of battery storage discharged power and the values of energy hub demand.

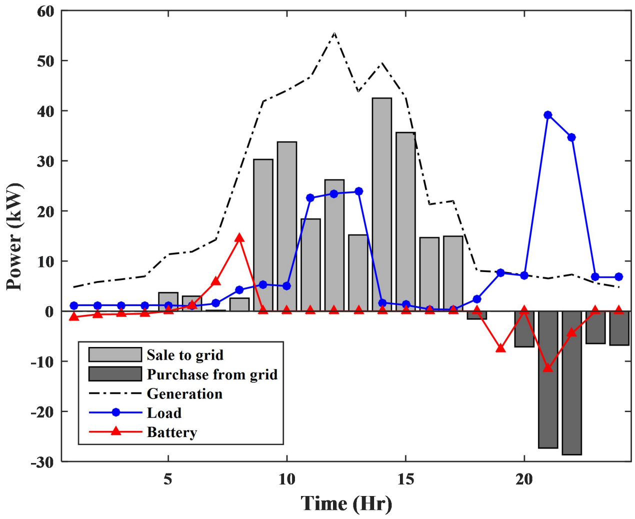

Figure 3. The optimization procedure results.

According to the electricity market, purchasing power from the wide-area electrical sub-network was so affordable for the system operator during the night hours to increase his/her profit. In addition, the battery storage remained in the standby mode during the times of selling power to the wide-area sub-network. In other words, it was very beneficial for the system operator to sell the generated power during the day hours and purchasing in the night hours instead of storing it to the battery.

The SOC of battery storage is shown in Figure 4. As illustrated in this figure, in the beginning of the day while the PV generation is very low and purchasing power form the wide-area electrical sub-network is expensive, the battery discharged some power. In the next hours of the day while the radiation of the sun is high enough, the PV system generation is at the proper value and it supplied the demand of village energy hub as well. In these hours of the day the battery storage charged to the fulfill value and it remained in the standby mode until the early hours of the night. Again, in the night hours of the day, by decreasing in the PV system generation, the SOC of battery decreased and the discharged power value assisted the local-area energy system in the supplying of the loads. As mentioned before the constraints of battery storage are satisfied completely. For example, the initial and final values of battery are remained equal to 5 kWh. In addition, according to the demands of village energy hub the proper size of the battery is equal to 25 kWh.

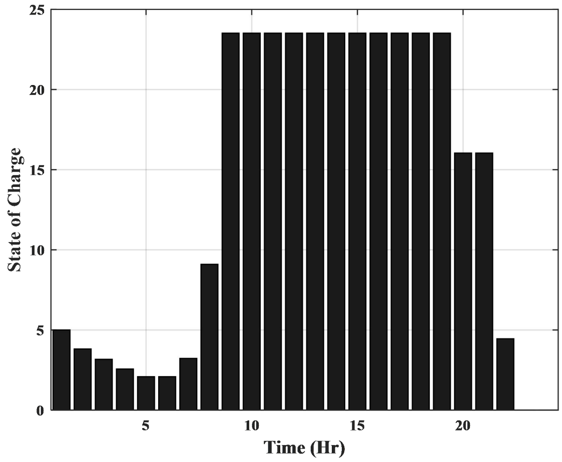

Figure 4. The SOC of battery storage.

The iteration of optimization problem is shown in Figure 5. In this figure the optimal scheduling problem is converged to a fixed value in which the maximum benefit of local-area energy system is reached to 3.6456$.

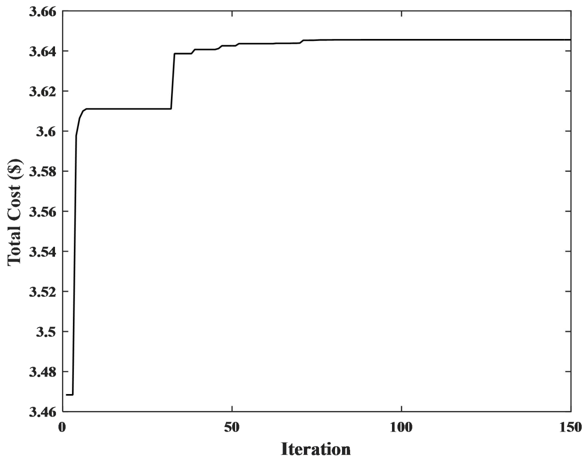

Figure 5. The iteration of optimization procedure.

The village energy hub consumes the electrical and heat power simultaneously. The village energy hub heat demand is shown in Figure 6. This heat power is supplied by the CHP technology. The CHP unit generate electrical power beside the heat and for producing these two output powers, it receives gas from the wide-area natural gas sub-network. The generated electrical and consumed natural gas of CHP unit is illustrated in Table 2.

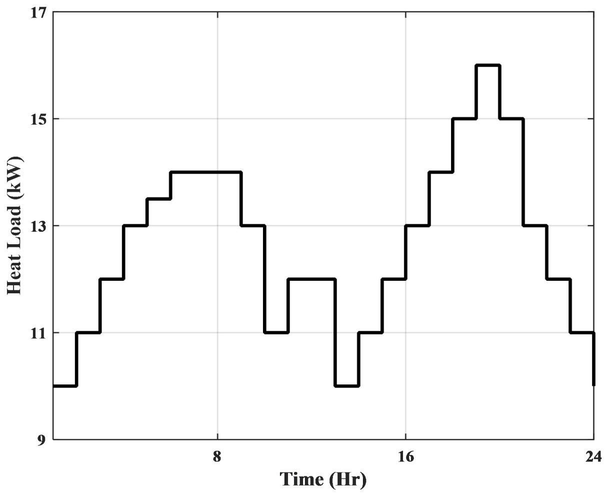

Figure 6. The village energy hub heat demand

Table 2. Electrical and natural gas powers of CHP unit

Hr.	P^{CHP}	f^{CHP}	Hr.	P^{CHP}	f^{CHP}
1	4.8000	1.4130	**13**	4.8000	1.4130
2	5.2800	1.5543	**14**	5.2800	1.5543
3	5.7600	1.6956	**15**	5.7600	1.6956
4	6.2400	1.8369	**16**	6.2400	1.8369
5	6.4800	1.9076	**17**	6.7200	1.9782
6	6.7200	1.9782	**18**	7.2000	2.1195
7	6.7200	1.9782	**19**	7.6800	2.2608
8	6.7200	1.9782	**20**	7.2000	2.1195
9	6.2400	1.8369	**21**	6.2400	1.8369
10	5.2800	1.5543	**22**	5.7600	1.6956
11	5.7600	1.6956	**23**	5.2800	1.5543
12	5.7600	1.6956	**24**	4.8000	1.4130

The exchanged power between the local-area and wide-area energy systems are expressed in Table 3. The first and second columns of this table shows the amounts purchased and sold powers from/to the wide-area energy system during the optimal scheduling problem. In addition, the next column of Table 3 shows the differences of battery storage charged and discharged power while the last column states the difference of generated and consumed power in the village energy hub. In the first times of the day, due to the fact that the loads of the village are higher than the generation, the energy hub operator decided to receive the shortage power from battery storage. During the times of the day that the PV generation is more than the load demand, the village operator decided to sell the surplus power to the wide-area electrical sub-network or may store it to the battery storage. According to the selling prices of electricity market it was more beneficial to sell the surplus amounts of generated power to the wide-area energy system.

Table 3. Energy system exchanged powers

Hr.	$P^{G}_{purchse}$	P^{G}_{sale}	P_{charge}-$P_{discharge}$	$P^{gen} - P^{load}$
1	0	-1.1847	-1.1847	0
2	0	-0.6447	-0.6447	0
3	0	-0.6031	-0.6031	0
4	0	-0.4823	-0.4823	0
5	0	0	3.6929	3.6929
6	0	1.1428	4.1344	2.9917
7	0	5.8674	6.0258	0.1585
8	0	14.4212	17.0129	2.5917
9	0	0	30.2707	30.2707
10	0	0	33.7661	33.7661
11	0	0	18.3930	18.3930
12	0	0	26.2054	26.2054
13	0	0	15.2039	15.2039
14	0	0	42.5062	42.5062
15	0	0	35.6396	35.6396
16	0	0	14.6793	14.6793
17	0	0	14.9519	14.9519
18	1.5658	0	-1.5658	0
19	0	-7.4785	-7.4785	0
20	7.1115	0	-7.1115	0
21	27.3131	-11.5841	-38.8972	0
22	28.6418	-4.4538	-33.0956	0
23	6.4589	0	-6.4589	0
24	6.7773	0	-6.7773	0

Table 4 states the prices of village energy hub. The first and second column of Table 4 shows the purchased and sold prices and accordingly in the last column of this table, the differences of these two columns are expressed as the benefits of village energy hub. The main object was to maximize the benefits of village energy hub as the local-area energy system.

Table 4. Village energy hub prices

Hr.	Purchased prices	Sold Prices	Benefits
1	0	0	-0.0707
2	0	0	-0.0777
3	0	0	-0.0848
4	0	0	-0.0918
5	0	0.1632	0.0678
6	0	0.1322	0.0333
7	0	0.0070	-0.0919
8	0	0.1146	0.0156
9	0	2.2037	2.1119
10	0	2.4582	2.3805
11	0	1.3390	1.2542
12	0	1.9078	1.8230
13	0	0.8894	0.8188
14	0	2.4866	2.4089
15	0	2.0849	2.0001
16	0	0.8587	0.7669
17	0	0.8747	0.7758
18	0.2036	0	-0.3095
19	0	0	-0.1130
20	0.9245	0	-1.0305
21	3.5507	0	-3.6425
22	3.7234	0	-3.8082
23	0.6549	0	-0.7326
24	0.6872	0	-0.7579

Conflict of interest

There is no conflict of interest for this study.

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