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ENERGY MANAGEMENT IN AN INDUSTRIAL TOWN USING THE CONCEPT OF VIRTUAL POWER PLANTS

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Abstract. Utilization of micro networks is highly noticed in recent years. Surveyed in this article, is a small network containing wind and solar power plants, fuel cells, super capacitors, batteries, and so forth. The network required load during 24 hours is supplied by available resources in a way that the cost would be minimum. The provisions related to CHP generators, wind power plants, batteries, heat storage, heat exchanger, and load supplying in the network are considered. In order to make the issue simpler, linearization method is used to convert the first and second degree equations. The problem is solved using GAMS software. The numeric study is done in two scenarios without concerning the pollution cost. Results showed in the case pollution cost is considered, the tendency to purchase electricity from the electricity market will increase. In addition, storages utilization leads to reduction of the network load ratio.

Keywords: MINLP, Virtual Power Plant, VPP

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1. INTRODUCTION

Concerning the increasing of distributed energy resources utilization in the level of power network and the necessity of their operation and management as well as trying to aggregately contribute these resources in electricity market, novel concepts have come to existence to reach this goal. In reference [1], a virtual power plant is defined with its various components. The main aim of this article is determining the place of distributed generation resources in virtual power plants. Defined in reference [2], is an energy hub and its different parts. In reference [3], utilization of renewable resources in virtual power plants is surveyed. In [4] the operation of a virtual power plant is investigated. Numeric studies in this survey are done on a real network. Voltage controlling in a network is analyzed in [5]. In this article, the surveying network consists several DGs with average voltage level.

2. PROBLEM DEFINITION

2.1. General structure of virtual power plants.

Figure 1 shows the general structure of the surveying power plant. This structure is composed of a CHP system, three DG units, interruptible and non-interruptible loads. The ownership and management of CHP and distributed generations are for VPP. The loads within the controlling area of VPP are supplied by a VPP retail rate. Furthermore, VPP considers the cost of unsupplied non-interruptible loads in its computations.

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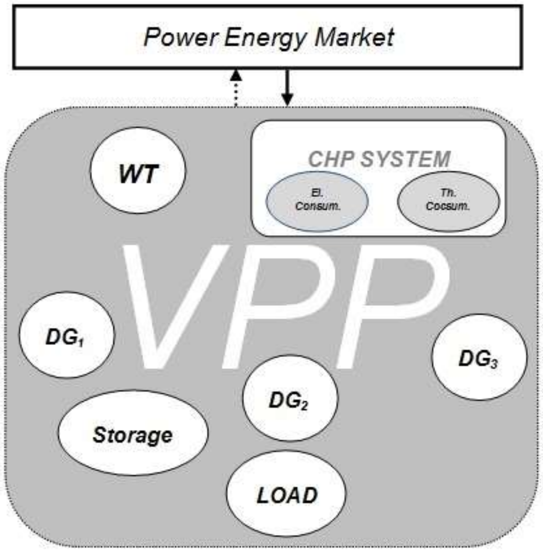

Figure 1. The structure of the surveying virtual power plant.

Following equations define the CHP system [7]:

The provision of production balance:

$$h_{boiler,t} = f_{boiler,t} . \eta_{boiler}$$
$$h_{CHP,t} = \frac{\alpha}{1+\alpha} \times f_{CHP,t} \qquad (1)$$
$$e_{CHP,t} = \frac{1}{1+\alpha} \times f_{CHP,t}$$

The provisions of fuel, electrical, and thermal balance are as followings:

$$f_{CHPsys,t} = f_{boiler,t} + f_{CHP,t}$$
$$e_{sys,t} = e_{demand,t} - e_{CHP,t} \qquad (2)$$
$$h_{d,t} = h_{boiler,t} + h_{CHP,t} + h_{f,t}$$

Heat storage balance:

$$h_{s,t} - h_{f,t} = h_{s,t+1} \qquad (3)$$

Laws relating to the boiler, CHP, and heat storage capacity:

$$f_{boiler,t} \le f_{\max\_boiler} \qquad (4)$$
$$f_{CHP,t} \le f_{\max\_CHP}$$
$$h_{s,t} \le h_{s\_\max}$$

The function which calculates the total cost of this system is as follows:

$$Cost_{CHPsys}(t)=\sum_{t=1:24}\left[f_{CHPsys,t}\cdot\rho_{ng,t}+e_{sys,t}\cdot\rho_{L,t}\right] \qquad (5)$$

In the equations above, the signs are considered as the followings.

Table 1. Signs relating to CHP system model.

System overall fuel used in hour t	$:f_{CHPsys,t}$	Produced heat by the boiler in hour t	$:h_{boiler,t}$
The amount energy exchanged with the network	$:e_{sys,t}$	Fuel used by the boiler in hour t	$:f_{boiler,t}$
System's required electrical load	$:e_{demand,t}$	Boiler efficiency	$:\eta_{boiler}$
System's required thermal load	$:h_{d,t}$	Produced heat by CHP in hour t	$:h_{CHP,t}$
The amount of heat stored in the storage	$:h_{s,t}$	Fuel used CHP in hour t	$:f_{CHP,t}$
The maxi8mum amount of heat stored in the storage	$:h_{s\_max}$	Produced electrical energy by CHP in hour t	$:e_{CHP,t}$
The price of electrical power exchanged with the network.	$:\rho_{L,t}$	Natural gas price per hour	$:\rho_{ng,t}$

2.2. The model of electrical energy storage

Electrical energy storage used in this study is electrochemical [8]. Following figure shows storage state before the analysis starts.

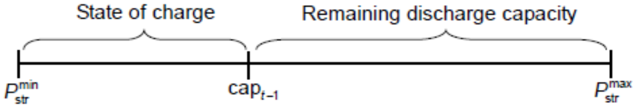

Figure 2. Storage state in T-1 [9].

If $P_{str,t}$ which shows the charging or discharging capacity in the T clock varies, its negative and positive values shows discharging and charging, respectively.

$$-\left(cap_0-P_{str}^{\min}\right)\le\sum_{k=1}^{t}P_{str,k}\le P_{str}^{\max}-cap_0,\forall t=1,2,\ldots,24. \qquad (6)$$

The rules relating to the electrical storage are as followings:

$$P_{str,t}\le R_{str-ch},:if\ \ storage\ \ is\ \ charged \qquad (7)$$
$$-P_{str,t}\le R_{str-dch},:if\ \ storage\ \ is\ \ discharged$$

The cost function of electrochemical storage is a linear function of charging and discharging capacity absolute value in every hour which is modeled as following.

$$C\left(P_{str}\right)=\alpha_{str}\left|P_{str}\right|+\beta_{str} \qquad (8)$$

In this relation, α_{str} and β_{str} are positive ratios of electrochemical storage linear cost function.

2.3. Wind turbine model

The output power of this unit is in relation with wind velocity and the parameters of power performance curve. Wind speed (V_w) can be estimated using Riley probability distribution function [9]. The turbine output power can be calculated by (2-21).

$$P_{WT}(v_w)=\begin{cases} 0 & 0\le v_w<v_{cutin} \\ P_{WT\max}\times\dfrac{(v_w-v_{ci})}{(v_{rated}-v_{ci})}m & v_{ci}\le v_w<v_{rated} \\ P_{WT\max}+\dfrac{P_{furl}-P_{WT\max}}{v_{cutout}-v_{rated}}\times(v_w-v_{rated}) & v_{rated}\le v_w<v_{cutout} \\ 0 & v_{cutout}\le v_w \end{cases} \qquad (9)$$

V_{cutin}, V_{cutout}, and V_{rated} are low cutting speed, high cutting speed, and nominal speed in terms of m/s, respectively. $P_{WT\max}$ and P_{furl} are the maximum turbine output power and output power in high cutting speed in terms of KW, respectively. Here, the value to M is considered 3.

2.4. Electrical loads model

In this model both of interruptible and non-interruptible loads are considered. If VPP uses interruptible loads, it should consider the cost of this work in its optimization calculation. The cost of unsupplied energy (C_{us}) for interruptible loads is modeled as the function of unsupplied energy amount (P_{us}).

$$C_{us}(t)=\alpha_{us}P_{us,t}^2+\beta_{us}P_{us,t} \qquad (10)$$

The limitation of P_{us} amount is as the following equation.

$$0\le P_{us,t}\le 0.1\times LOAD_t \qquad (11)$$

2.5. Distributed generation

These units are located in the controlling area of VPP. The ownership and management of these resources are through VPP. The technologies considered for distributed generation are fuel cells, micro turbines, and diesel generators [10]. The cost of energy produced for these DGs is modeled using the following relation.

$$C_{DG_i}(t)=a_{DG_i}P_{DG_{i,t}}{}^2+b_{DG_i}P_{DG_{i,t}} \qquad i=1,2,3 \qquad (12)$$

Following regulations are considered for distributed generations:

- **Limitation of DG output power**

$$x_i^t.P_{\min_i}\le P_{DG_{i,t}}\le x_i^t.P_{\max_i} \qquad (13)$$

- **The minimum time for being on and off**

$$\left[U_{i,t-1}^{up}-MUT_i\right]\times\left[x_i^{t-1}-x_i^t\right]\ge 0 \qquad (14)$$

$$\left[U_{i,t-1}^{down}-MDT_i\right]\times\left[x_i^t-x_i^{t-1}\right]\ge 0$$

In this survey, all the generation units including electrical and thermal energy producers, and pollution costs are taken into account. Atmospheric pollutants such as SO2, CO2, and CO2 are produced by burning fossils fuels. The model of these pollutants can be considered as (2-28) [9].

$$E(P_{i,t}) = 10^{-2}(\alpha_i + \beta_i P_{i,t} + \gamma_i P_{i,t}^2) \tag{15}$$

In this relation, $P_{i,t}$ is the output power of the i^{th} generators and α, β, and γ are the ratios which describe each generator attributes.

3. TARGET FUNCTION

The first approach to the problem of VPP's profit maximizing optimization is furnished by its energy exchanges with electricity market and supplying loads in its controlling area. The target function optimized by CCC can be stated as the following.

$$\begin{aligned}
&\sum_{t=1:24} \rho_{L,t}.(Load_t - P_{us,t}) - \sum_{t=1:24} \rho_{e,t}.P_{e,t} - \\
&\sum_{t=1:24} \left[f_{CHPsys,t}.\rho_{ng,t} + e_{CHPsys,t}.\rho_{L,t} + E(e_{CHPsys,t}) \right] \\
&- \sum_{\substack{i=1:3 \\ t=1:24}} \left[C_{DG_i,t} + E(P_{DG_i,t}) \right] - \sum_{t=1:24} C_{us,t} - \sum_{t=1:24} C\left(P_{str,t}\right) \\
&Load_t = LOAD_t - P_{WT,t} \\
&P_{e,t} + \sum_{i=1:3} P_{DG_i,t} + e_{CHPsys,t} - P_{str,t} = Load_t - P_{us,t} \qquad ,\forall t = 1, 2, ..., 24. \\
&h_s(0) = h_s(24) \\
&\left|P_e\right| \le P_{exch}^{\max}
\end{aligned} \tag{16}$$

In the relation above, $\rho_{L,t}$, $\rho_{e,t}$, $LOAD_t$, $Load_t$, $h_s(0)$, and $h_s(24)$ are VPP retail rate, energy price in electricity market in each hour, system total load, system load after subtracting wind turbine production rate, thermal energy stored in heat storage at the first of the time period and the thermal energy stored in the storage at the end, respectively. P_e is the power swipped between virtual power plant and electricity market. The positive and negative values of $P_{exch}^{\max}$ show the power bought and the power sold to the electricity market based on maximum contract capacity between VPP and the upstream network, respectively.

4. NUMERICAL STUDY

4.1. The inputs of the optimization problem

A. The characteristics of CHP system components

Demonstrated in table 2, are the attributes of combined heat and power system.

Table 2. CHP system components traits.

$f_{\max\_CHP} = 187.5kW$, $f_{\max\_boiler} = 192.3kW$	The maximum input fuel DB for CHP and boiler
$\eta_{boiler} = 0.85$, $\eta_{CHP} = 0.8$	Total efficiency of boiler and CHP energies
$h_{s\_\max} = 107.7kWh$, $h_s(0) = 57.7kWh$	The maximum capacity of heat storage and its initial heat level
$\alpha = 2$	The ratio of thermal power to electrical power of CHP unit
$\rho_{ng} = 5.5$ (Monetary Unit/kWh)	Gas price

The thermal and electrical demand of CHP system is presented in figure 3.

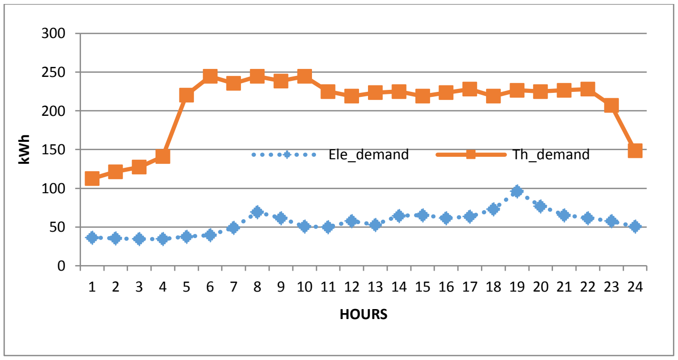

Figure 3. Electrical and thermal load of CHP system

The total predicted load during 24 hours in addition to VPP retail rate and electricity market price are brought in figures 4 and 5, respectively.

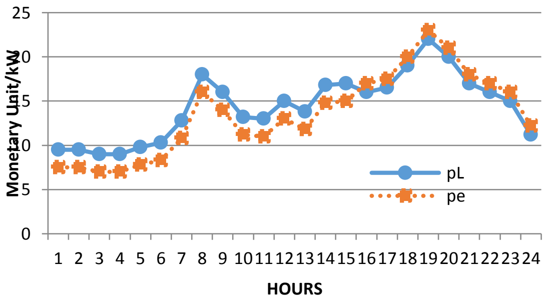

Figure 4. VPP retail rate (p_l) and electricity market price (p_e).

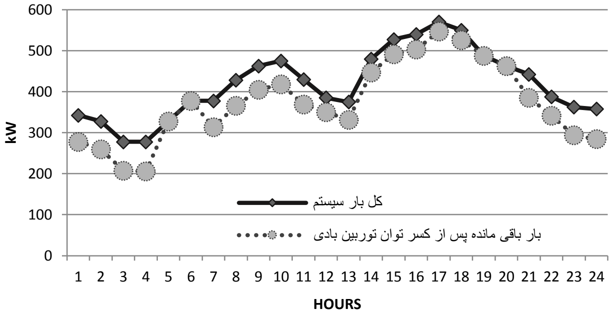

Figure 5. System total load (LOAD_t) and the load remained after subtraction of wind turbine production power (Load_t).

B. Distributed generation resources characteristics

The ratios of production and pollution cost functions as well as attributes of distributed generation resources are displayed in table 3.

Table 3. The ratios of production and pollution cost functions as well as characteristics of distributed generation resources.

	a_{DG}	b_{DG}	α_{DG}	β_{DG}	γ_{DG}	MUT	MDT	U_0	S_0	V_0	$P_{\min}$	$P_{\max}$
DG$_1$	0/03	4/1	0/2	10	50	3	3	0	1	0	0	200
DG$_2$	0/02	3/1	0/4	12	62	2	2	2	0	1	0	150
DG$_3$	0/025	3/2	0/3	11	55	1	1	1	0	1	0	150

C. Electrical energy storage characteristics

Shown in figure 4, are the attributes of electrochemical energy storage used in this survey.

$P_{str}^{\max} = 65\ kWh$	The capacity of the installed electrochemical storage
$R_{str-ch} = 18\ kW$, $R_{str-dch} = 18\ kW$	The maximum rate of charging and discharging
$cap_0 = 5\ kWh$	Battery charge at the first
$P_{str}^{\min} = 0$	Minimum battery charge
$\alpha_{str} = 0.1$, $\beta_{str} = 1$	The ratios of electrochemical storage cost function

Figure 4. Electrical energy storage characteristics.

D. Wind turbines characteristics

BWC Excel-R/48 is the surveying turbine model. The nominal capacity of this turbine is 7.5 kW. Information needed for a wind turbine is presented in table 5. In this survey, 10 numbers of these turbine are used which give the overall nominal power of 75 kW.

$P_{rated} = 7.5\ kW$	Turbine nominal power
$v_{cutin} = 3\ m/s$, $v_{cutout} = 25\ m/s$	Wind speed lower and upper limit
$v_{rated} = 11\ m/s$	Turbine nominal speed
$P_{WT\max} = 8.1\ kW$	Turbine maximum output power
$P_{furl} = 5.8\ kW$	Output power in high cutting speed

Figure 5. Characteristics of a wind turbine unit.

Wind speed characteristics is shown for one year in figure 1. In this study, a 24-hour period of this trait has been considered.

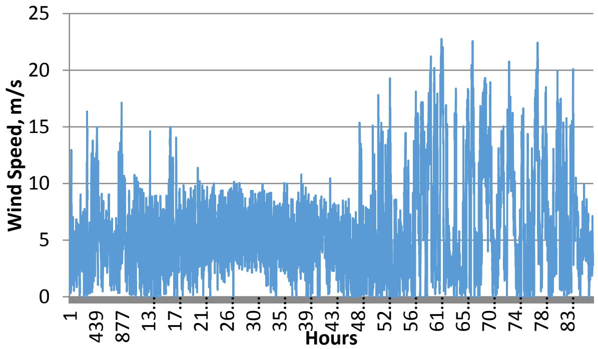

Figure 6. Wind speed characteristic during one year.

4.2 Optimization problem solving results

In this study, the problem of optimization is solved for two scenarios. In the first scenario, pollution cost has not considered, however; in the second one, this cost in addition to other costs have been noticed. Therefore, VPP profit has been obtained for the two scenarios per hour. Solving period of each scenario is lower than 0.015 second. Figure 1 demonstrates the VPP profit per hour for both of the scenarios. Analyzing the results, it is obvious that VPP profit is significantly more when pollution cost has not been considered, if compared with the state that the costs have been taken into account. The overall profits for the first and second scenarios are 44220.78 and 35523.85 currency.

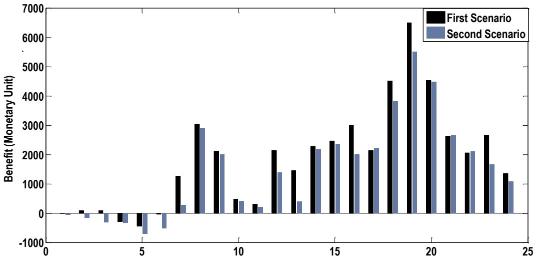

Figure 7. Hourly VPP profit for two different scenarios.

The amount of boiler thermal energy, CHP unit, and the amount of energy stored by thermal storage are presented in figure 8, 9 and 10, respectively.

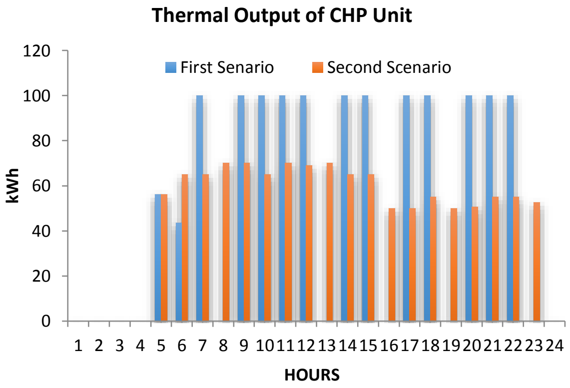

Figure 8. Energy produced by CHP unit.

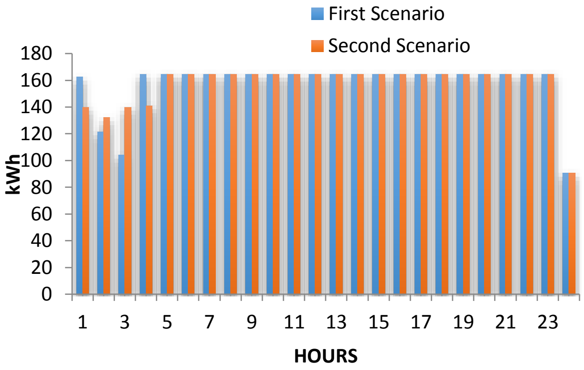

Figure 9. Thermal energy produced by the boiler.

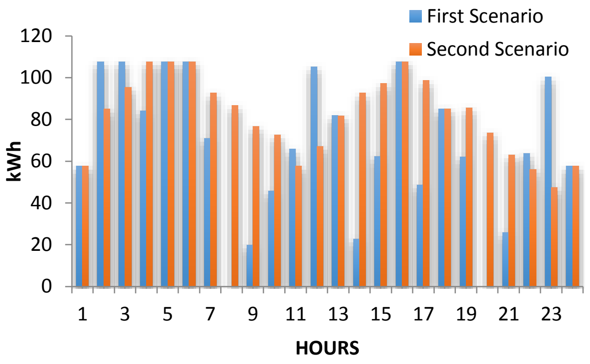

Figure 10. Heat stored in the tank.

Solving the optimization problem, the amount of energy exchanged with electricity market per hour will be obtained. Virtual power plant is able to determine its pricings in the electricity market using these strategic results. Presented in figure 11, is the amount of energy exchanging with the electricity market per hour.

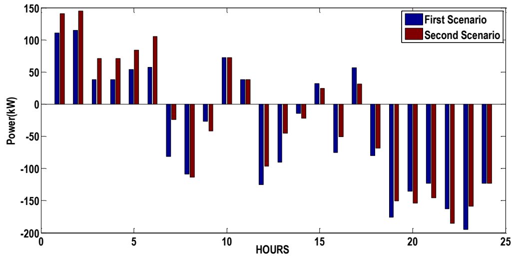

Figure 11. The amount of energy exchange with electricity market per hour.

The unsupplied energy and electrochemical storage charging state are the same in both of the scenarios. Figure 12 and 13 display charging/discharging state of electrochemical storage and the amount of unsupplied energy, respectively.

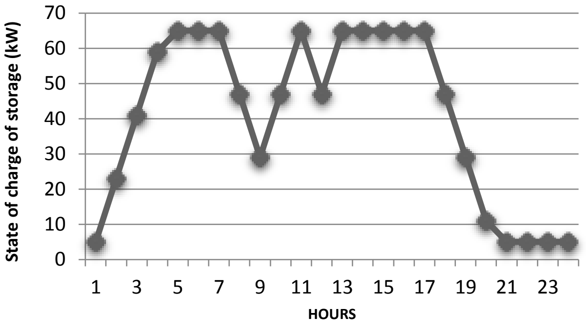

Figure 12. Battery charging and discharging state.

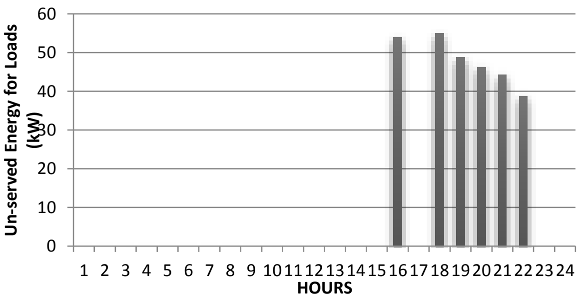

Figure 13. The amount of unsupplied energy.

Results analysis showed VPP profit is more in the case that pollutions costs are not considered in the calculations, however; this amount drops down as these costs are taken into account. If compared with the first scenario, the amount of energy bought from the electricity market is greater in the second scenario in different hours. It is due to pollution costs for resources in VPP controlling area which increase as the resources' generation does. As a result, VPP's tendency for buying the required energy to supply its loads will be increased. In addition, on average, the amount energy sold in in the first scenario is greater than in the second one in various hours.

5. CONCLUSION

Analyzing the results, utilization of various resources in micro networks requires optimization problem to be solved. Furthermore, models used to describe the network components have significant effects on final results. Results of the article showed that the tendency to use fossil resources decreases if pollution costs are noticed. In addition, storages utilization leads to improvement of network load ratio.

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