Energy Management of Microgrid in Smart Building Considering Air Temperature Impact

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***Abstract*—The economic dispatch is based on finding the optimal combination of all the energy resources of the microgrid. In this paper, a smart building microgrid model is supplied by diesel generators, PV, energy storage system (ESS), and main grid. The objective of this paper is to manage the generation resources which operate over a time horizon while satisfying many key constraints in low cost. In order to achieve better energy efficiency in the building, this paper proposed an improved energy management operation. In the proposed operation, the economic dispatch operation ED is presented according to such aspects as air temperature impact, the resistance of building shell, time horizon and so on. The accuracy and feasibility of the proposed energy management operation has been validated by GAMS simulation results.**

***Keywords*—Air temperature impact; economic dispatch; microgrid; Smart building**

Nomenclature

a, b, c	The cost function coefficients, \$/ kW^{2}h, \$/ kW and \$/h, respectively.
C_{air}	Cooling / Heating capacity of the indoor air (kWh/°C).
$C_{buy}(t)$, $C_{sell}(t)$	Purchased and Sold electricity prices at dispatch period, respectively (\$ US).
COM_i	Maintenance and operation costs (\$US).
$C_T(P)$	The total cost function of the connected Microgrid (US \$).
$e_{batt}(t)$	Battery energy quantity at dispatch period t (kWh).
$e_{batt-cap}$	Battery capacity (kW).
$e_{critical}$	The electrical consumed energy of critical loads (kW).
$e_g(t)$	Grid energy quantity at dispatch period t (kWh).
$e_{HVAC}(t)$	Energy consumption of HVAC system at dispatch period t (kWh).
$e_{light}(t)$	Energy consumption of lighting system at dispatch period t (kWh).
$e_{solar}(t)$	Solar energy quantity at dispatch period t (kWh).
$F_i(P(t))$	Fuel cost of each distributed energy resource.
G_{ac}	Incident solar irradiation (*W/m*^{2}*.)*.
G_{STC}	Solar irradiance at STC (1000 *W/m*^{2}*, 25* c°).
i	Generator index.
K	Temperature coefficient. K_{COMi} Proportional constant of the generation unit *i*.
K_{COM_i}	Represents the operation and maintenance costs (\$ US).
n	Total number of distributed energy resources DERs.
$P(t)$	Output power of each distributed generation (kW).
$P_{air}(t)$	Thermal power needed to keep the temperature indoor at a desired value (kW).
$P_{batt}(t)$	Power from battery at dispatch period *t* (kW).
$P_{ch}^{\max}(t)$, $P_{ch}^{\min}(t)$	The maximum and minimum battery charge, respectively (kW).
$P_{di}(t)$	The output power of the diesel generator at dispatch period *t* (kW).
$P_{diesel}(t)$	Power from diesel generators at dispatch period *t* (kW).
$P_{dis}^{\max}(t)$, $P_{dis}^{\min}(t)$	The maximum and minimum battery discharge, respectively (kW).
$P_{heating}(t)$, $P_{cooling}(t)$	Heating and Cooling power needed to adjust the indoor temperature at desired value, respectively (kW).
$P_{HVAC}(t)$	HVAC load demand (kW).
$P_i^{\max}$, $P_i^{\min}$	Maximum and minimum output power of distributed generation unit, respectively (kW).
$P_g(t)$	Power purchased/sold from/to utility grid at dispatch period *t* (kW).
$P_L(t)$	Power demand (the electrical load) at dispatch period *t* (kW).
$P_{light}(t)$	Lighting load demand (kW).
P_{PV}	The output power of PV module (kW).
$P_{sell}(t)$, $P_{buy}(t)$	Sold and Purchased power electricity, respectively (kW).
P_{solar}	Output power of PV plant at dispatch period *t* (kW).
P_{STC}	The maximum power of PV at STC (kW)
R	Thermal resistance of the building envelope (°C /kW).
T	Total interval time.
t	Time interval.

T_d	Desired indoor temperature (°C).
T_i, T_c	The reference temperature and cell temperature, respectively (c°).
$T_{in}(t)$, $T_{out}(t)$	The indoor and outdoor temperature at dispatch period t, respectively (°C).
$T_{in-\min}, T_{in-\max}$	Minimum and Maximum indoor temperature (°C).
$x_{batt}(t)$	Battery state of charge (SOC).
$x_{batt-\min}$	The lower limit of the SOC.
Greek symbols	
Δ	Time interval (one hour).
τ	Time period.
τth	Thermal constant.

I. INTRODUCTION

Energy-saving solutions in building sector are divided into two types: passive and active. The passive solutions conclude permanent ways of energy efficiency like insulating the building envelope and using double or multiple glazing. On the other hand, the active solutions contain automated systems like lighting system with natural sunlight control, the thermal load which follows the desired internal temperature, etc. [1]. These types of buildings are then called the smart buildings. The smart building (microgrid) contains many distributed energy resources such as the renewable resources (PV), energy storage devices and could be connected to the utility grid. Traditional generators are also used as reserve generation. These resources will provide the energy to different types of loads in the building [2]. The function of the smart building is to implement a safe, comfortable, economical, environment friendly and energy efficient living environment [3].

The economic dispatch is based on finding the optimal combination of all the energy resources of the microgrid in order to reduce the whole cost while considering the supply-demand and other operation constraints [4]. A lot of work has been done in this field. In [5], [6] the authors assumed a low energy consumption building microgrid supplied by different distributed generations, the thermal and electrical load profiles were assumed. Reference [7] assumed a building provided with controllable electrical loads and smart meters in order to employ a smart control for the microgrid. They formulated a temperature reliant thermal load model, but their given equation to calculate the thermal power needed to keep the indoor temperature at a desired value. That is only correct for heating load. In [8] the authors presented a microgrid operates in the islanded state. The thermal load was considered constant and storage system wasn't discussed. Authors in [9], [10] presented a renewable based-microgrid and battery, the cogeneration or micro-turbine problems in this study were not mentioned. In [11], [12] the cost function of the micro-turbine was assumed as a linear function but in this paper, it is given as a quadratic equation. Reference [13] presented many aspects such as scheduling, energy exchange with utility grid and DSM.

Reference [14] used HOMER software in grid-connected mode. Reference [15] presented an isolated microgrid which supplies three remote areas and the same case was discussed in Budapest [16]. However, these papers only included the electrical assessment. Meanwhile, The energy storage devices with schedulable loads can be arranged simultaneously [2]. The day-ahead energy management operation was discussed in many papers such as [5], [6] and [17]. Two days ahead in [18], 15 minutes ahead in [19].

On considering the abovementioned problems, the objective of this paper is to manage the generation resources to minimize the total cost of electricity in the building. To achieve that, an improved energy management operation is proposed. Both electrical and thermal loads are taken into consideration in the proposed method. Moreover, 24 hours ahead in addition to 5 minutes ahead economic dispatch is discussed with respect to the power balance and the operation constraints. This operation is done under many key constraints such as electrical power balance, power generation, utility grid power price and ESS control constraints. The air temperature impact on the energy management of smart building microgrid is taking into consideration. Therefore, the impact on both heating and cooling loads is investigated. Meanwhile, the effect of the thermal resistance of building shell (envelope) on the total cost of consumed energy is studied in detail.

II. ENERGY MANAGEMENT MODEL OF THE KEY ELEMENTS IN SMART BUILDING MICROGRID

As displayed in Fig. 1 an electrical network interconnects many generation units (on the supply side) with energy consumption elements (on the demand side) and energy storage devices. The figure represents the studied building microgrid in grid-connected mode.

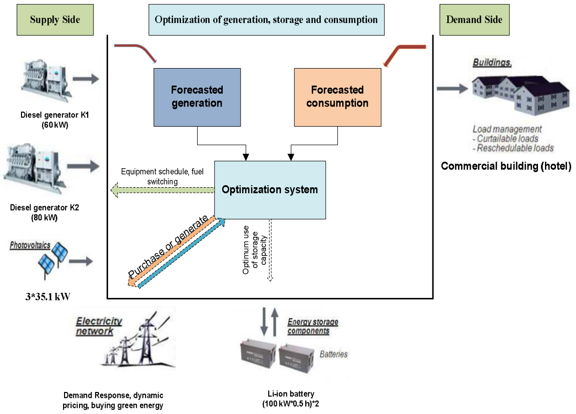


Fig. 1. Schematic Representation of the Connected Microgrid to the Smart Building

A. *Cost Function of Diesel Generators*

The studied microgrid includes two diesel generators K1, K2. The cost function is given by nonlinear quadratic equation.

$$F_{DGi}(t) = a P_{di}^{2}(t) + bP_{di}(t) + c \qquad (1)$$

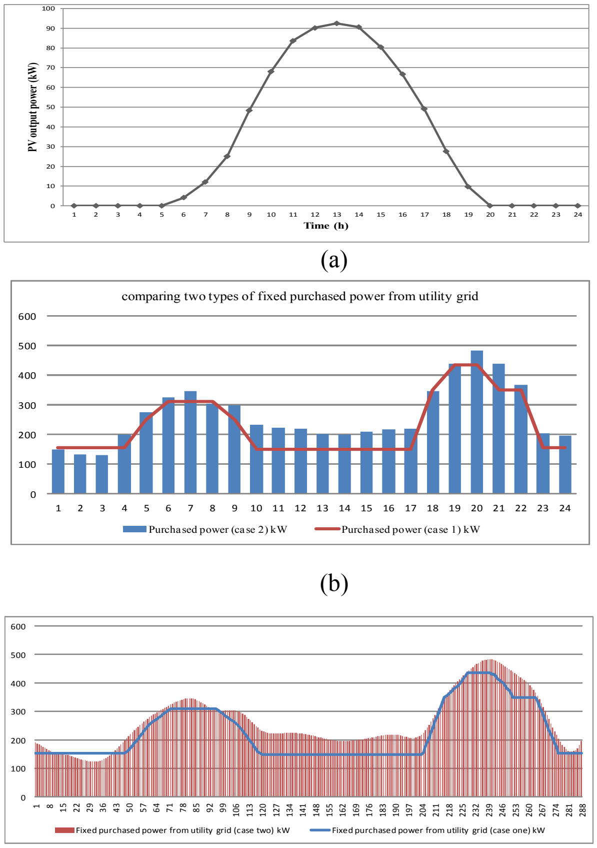
B. *PV System Data*

Microgrid system contains three PV power plants (3×35.1 kW). Solar radiation data is converted into power output using (2) and solar irradiation profile. The calculated PV output power is given in Fig. 2.

$$P_{PV} = P_{STC} \frac{G_{ac}}{G_{STC}} (1 + K(T_c - T_i)) \qquad (2)$$

C. *Purchased Power from Utility Grid*

Two cases of utility power grid will be discussed. The first one with fixed power curve from utility grid (In this case also two fixed purchased power from utility grid will be studied). Day-ahead ED and 5-minutes ED are illustrated in Fig. 2 (a). The other case is variable power from the utility grid, which is deeply affected by electricity prices, it is given in TABLE 1.



(a)

(b)

(c)

Fig. 2. (a) PV output. Next: Fixed purchased Power from Utility Grid. (b) In case day-ahead. (c) 5 minutes ahead ED

TABLE 1. ELECTRICITY PRICE

Period	**Time**	**Purchase price ($/ kW)**	**Sale price ($/ kW)**
Peak	10.00-17.00	0.08	0.06
Off peak	The rest time	0.04	0.06

D. *Energy Storage System (ESS)*

Rechargeable Li-ion battery are used, selected ESS is (100 kW × 0.5 h) × 2.

TABLE 2. BATTERY DATA

ESS parameters	**Description**	**Electrical**
Charging efficiency	The useful portion of input energy to storage	0.96
Maximum charge rate	Maximum portion of added rated capacity to the storage during an hour	0.25
Maximum discharge rate	Maximum portion of withdrawn rated capacity from storage during an hour	0.25
Minimum state of charge	rated capacity portion	0.3

E. *End Use Load (Demand Side)*

Two load curves will be discussed. First, the electrical load (electrical demand is given in TABLE 3). Secondly, the thermal demand (air conditioning load for both space cooling and space heating) will be calculated.

TABLE 3. ELECTRICAL DEMAND PROFILE

Time (h)	**Electricity Load (kW)**	**Time (h)**	**Electricity Load (kW)**
1	215	13	330
2	205	14	340
3	200	15	343
4	280	16	360
5	350	17	350
6	425	18	495
7	470	19	560
8	435	20	575
9	425	21	503
10	350	22	444
11	375	23	270
12	360	24	240

III. PROBLEM FORMULATION

General Mixed Integer Programming is used to solve the problem and executed by GAMS.

A. Objective Function

$$\min C_T(\mathrm{p}) = \sum_{t=1}^{T} \left(\begin{array}{l} \sum_{i=1}^{n} \left[F_i(\mathrm{P(t)}) + \mathrm{COM}_i(\mathrm{P(t)}) \right] + \\ C_{buy}(\mathrm{t})\mathrm{P}_{buy}(\mathrm{t}) - \mathrm{C}_{sell}(\mathrm{t})\mathrm{P}_{sell}(\mathrm{t}) \end{array} \right) \tag{3}$$

$$COM_i = \sum_{t=1}^{T} COM_i(\mathrm{P(t)}) = \sum_{t=1}^{T} K_{COMi}(\mathrm{P(t)}) \tag{4}$$

B. Constraints

1) Electrical Power Balance

The generated power in the supply side must be equal to the power on the demand side; it can be presented as follows

$$P_{buy}(\mathrm{t}) - P_{sell}(\mathrm{t}) + P_{solar}(\mathrm{t}) + P_{diesel}(\mathrm{t}) - P_{batt}(\mathrm{t}) = P_L(\mathrm{t}) \tag{5}$$

$$P_g(\mathrm{t}) = P_{buy}(\mathrm{t}) - P_{sell}(\mathrm{t}) \tag{6}$$

$$e_g(\mathrm{t}) + \mathrm{e}_{solar}(\mathrm{t}) + \mathrm{e}_{diesel}(\mathrm{t}) - \mathrm{e}_{batt}(\mathrm{t}) = \mathrm{e}_{light}(\mathrm{t}) \tag{7}$$

2) Power Generation Constraint

To ensure the stability of system operation, each power generation has stringent upper and lower limits;

$$P_i^{\min} \le P_i \le P_i^{\max}, \forall i = 1,2,3,.....N \tag{8}$$

3) Electricity Cost from Utility Grid

$$C_T^p(\mathrm{t}) = \begin{Bmatrix} C_{buy}(\mathrm{t})\mathrm{P}_g(\mathrm{t})......\mathrm{if}..\mathrm{P}_g \ge 0 \\ C_{sell}(\mathrm{t})\mathrm{P}_g(\mathrm{t})......\mathrm{if}..\mathrm{P}_g < 0 \end{Bmatrix} \tag{9}$$

4) ESS Control Constraints

- Input and output power capacities

$$P_{batt}(\mathrm{t}) \in \left\{ 0, \left[-P_{dis}^{\max}, -P_{dis}^{\min} \right], \left[P_{ch}^{\min}, P_{ch}^{\max} \right] \right\} \tag{10}$$

- SOC constraint

$$x_{batt-\min}(\mathrm{t}) = \frac{e_{critical}}{e_{batt-cap}} \le x_{batt}(\mathrm{t}) \le 1 \tag{11}$$

- SOC dynamic

$$x_{batt}(\mathrm{t+1}) = \mathrm{x}_{batt}(\mathrm{t}) + \frac{P_{batt}(\mathrm{t})\tau}{e_{batt-cap}} \tag{12}$$

IV. IMPROVED MODEL WITH AIR TEMPERATURE IMPACT

The outdoor temperature affects the amount of required energy to keep the indoor temperature at the desired level.

A. The Demand-Supply Balance

The balance between generation and demand must be met as follows

$$\begin{bmatrix} P_{buy}(\mathrm{t}) - P_{sell}(\mathrm{t}) + P_{solar}(\mathrm{t}) + \\ P_{diesel}(\mathrm{t}) - P_{batt}(\mathrm{t}) \end{bmatrix} = P_{light}(\mathrm{t}) + P_{HVAC}(\mathrm{t}) \tag{13}$$

$$e_g(\mathrm{t}) + \mathrm{e}_{solar}(\mathrm{t}) + \mathrm{e}_{diesel}(\mathrm{t}) - \mathrm{e}_{batt}(\mathrm{t}) = \mathrm{e}_{light}(\mathrm{t}) + \mathrm{e}_{HVAC}(\mathrm{t}) \tag{14}$$

B. The Required Power for Heating/Cooling

The temperature inside the building is given by [7].

$$T_{in}(\mathrm{t+1}) = \begin{bmatrix} \mathrm{T}_{in}(\mathrm{t})\exp(-\Delta / \tau th) \\ +(\mathrm{R}.\mathrm{P}_{air}(\mathrm{t}) \\ +\mathrm{T}_{out}(\mathrm{t})).(1-\exp(-\Delta / \tau th)) \end{bmatrix} \tag{15}$$

$$\tau th = R.C_{air} \tag{16}$$

From (15)

$$P_{heating}(\mathrm{t}) = \frac{T_{in}(\mathrm{t+1}) - [\mathrm{T}_{in}(\mathrm{t})\exp(-\Delta / \tau th)] - [\mathrm{T}_{out}(\mathrm{t}).(1-\exp(-\Delta / \tau th))]}{R.(1-\exp(-\Delta / \tau th))} \tag{17}$$

$$P_{cooling}(\mathrm{t}) = \frac{T_{in}(\mathrm{t+1}) - \mathrm{T}_{in}(\mathrm{t}) + \mathrm{T}_{out}(\mathrm{t}) - (\mathrm{T}_{in}(\mathrm{t})).(1-\exp(-\Delta / \tau th))}{R.(1-\exp(-\Delta / \tau th))} \tag{18}$$

C. The Internal Building Temperature

$$T_{in-\min}(\mathrm{t}) \le \mathrm{T}_{in}(\mathrm{t}) \le \mathrm{T}_{in-\max}(\mathrm{t}) \tag{19}$$

V. SIMULATION RESULTS

The case study is a smart commercial building in San Francisco, US [19]. Two diesel generators: (60 kW and 80 kW). Three PV: (3×35.1 kW) and two Li-ion batteries. The smart building microgrid is operating in a grid-connected mode so it can purchase or sell energy according to load demand and electricity prices. In order to give a comprehensive analysis of microgrid system of the smart building, ten case studies under different conditions were presented, as shown in TABLE 6. The proposed model is solved by a 2.20 GHz personal computer using GAMS software.

TABLE 4 THERMAL PARAMETERS PROFILE

Parameter	Value	Unit
Desired temperature	24	(°C)
R	10	(°C /kW)
C_{air}	0.525	(kWh/°C)
efficiency	50 %	------
Tin min	22,23	(°C)
Tin max	25,26	(°C)

TABLE 5 COST FUNCTION PARAMETERS OF DIESEL GENERATORS

P_{min} kW	P_{max} kW	Maintenance & operation Cost $/ kW	Start up cost($)	Coefficients of cost function		
				a $/ kW ^{2}h	b $/ kW	c $/h
12	60	0.001258	0.25	0.00033	0.0364	0.6339
16	80	0.001260	0.25	0.00027	0.0378	0.649

TABLE 6 TEN CASE STUDIES WITH DIFFERENT MODES

Case	Day ahead/5 Minutes Ahead ED	Fixed or Variable Curve of Utility Grid	Heating or Cooling with Air Impact
1	Day ahead	Fixed curve 1	-
2	Day ahead	Fixed curve 2	-
3	Day-ahead	Variable curve	-
4	5 minutes ahead	Fixed curve	-
5	5 minutes ahead	Variable curve 1	-
6	5 minutes ahead	Variable curve 2	-
7	Day-ahead	Fixed curve 1	Air impact on heating load
8	Day-ahead	Variable curve	Air impact on heating load
9	Day-ahead	Fixed curve 1	Air impact on cooling load
10	Day-ahead	Variable curve	Air impact on cooling load

A. Day-Ahead ED with Fixed Power Curve of Utility Grid (case 1)

The total cost function value was $ 444.019 US, the distributed energy resources (DERs) outputs are displayed in Fig. 3, The charging hours mostly happen during the off-peak time and only three hours during on-peak time (13:00-15:00 pm) because more power is produced by diesel generators and PV system. Electricity power is always purchased.

B. Day-Ahead ED with Air Temperature Impact on Cooling Load (case 10)

The total cost is $ 427.274 US when thermal resistance of the building shell is 10 (°C /kW). The required power for space cooling in order to keep the indoor temperature at desired value is displayed in Fig. 4.

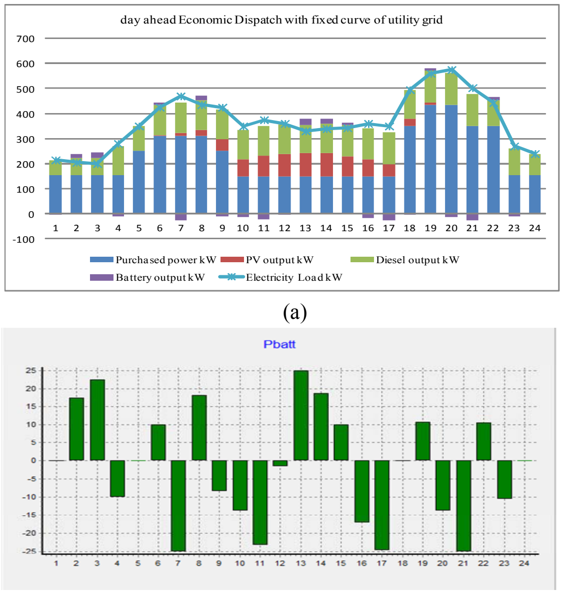
The power from the utility grid is always positive, so it's always purchased in order to meet the high load demand. The diesel generators operate with high power during the on-peak time (high electricity price) which is the same as temperature peak time during the day. Therefore, to meet the total demand. First, the diesel generators will produce more power because it's more economical at this time. The relation between the thermal resistance of the building shell and the total cost is presented in TABLE 7.

The resistance value of the building shell is restricted between maximum and minimum limits can't be exceeded, although higher value means lower total cost. On the other hand, raise the resistance value means increasing the insulation of building envelope which reduces convective heat transfer significantly, but the insulation has certain practical thickness can't be exceeded also. So by test, the resistance value can be true between 4 and 26 (°C/kW). The thermal load demand is related to the outdoor temperature and the indoor required temperature.

By adjusting the desired temperature at 24 (°C) the required thermal heating power and thermal cooling power were achieved, the case studies are compared as displayed in TABLE 8.

TABLE 7 RELATION BETWEEN THE RESISTANCE OF BUILDING SHELL AND THE TOTAL COST

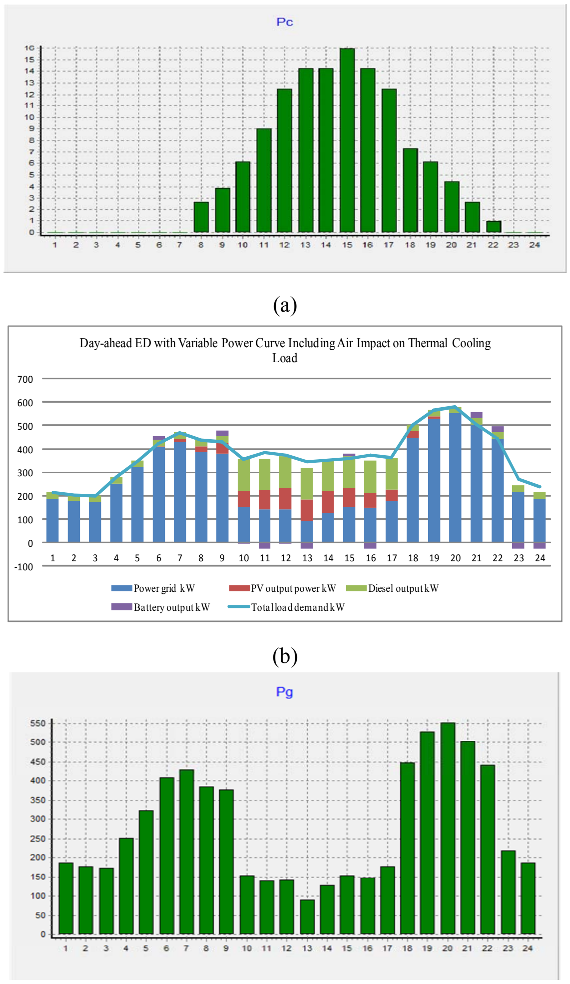
Resistance of the building shell R (°C/kW)	Total cost Z ($ US)
R ≥ 27	Not practical
20	444.532
18	444.863
16	445.374
14	445.998
12	446.952
10	448.233
8	450.226
6	453.519
4	460.258
2	Not valid



(a)

(b)

Fig. 3. (a) Day ahead ED-output power of energy sources. (b) Battery output (positive values mean charging)/ kW

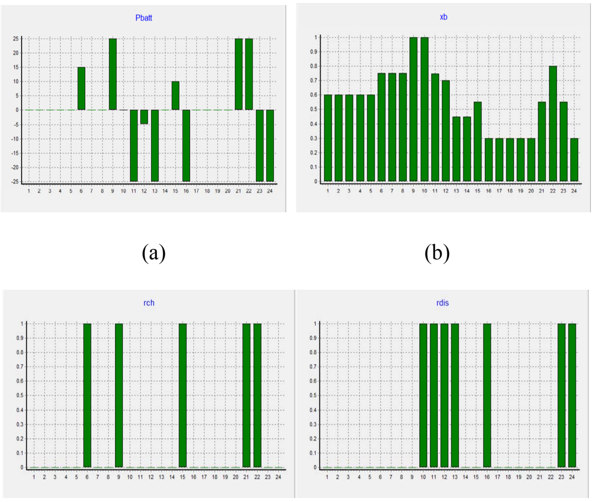


(a)

(b)

(c)

Fig. 4. (a) Required power for cooling load/ kW. (b) ED with air impact-output power DERs. (c) Purchased/Sold power from grid/ kW



(a)

(b)

(c)

(d)

Fig. 5. (a) Battery output/kW. (b) SOC. (c) Charging periods. (d) Discharging periods

TABLE 8 SUMMARY OF CASE STUDIES

Case study	**Total cost $ US**	**Battery charge**	**Battery discharge**
Case 1	444.019	9 hours	13 hours
Case 2	441.457	8 hours	12 hours
Case 3	418.245	5 hours	7 hours
Case 4	441.969	48 periods	80 periods
Case 5	413.483	17 periods	17 periods
Case 6	319.000	68 periods	71 periods
Case 7	448.233	10 hours	13 hours
Case 8	421.217	5 hours	7 hours
Case 9	453.612	8 hours	14 hours
Case 10	427.274	5 hours	7 hours

VI. CONCLUSION

Microgrid for buildings combines the operation of electrical energy and thermal energy supply and demand to minimize the total cost. In this paper, an improved energy management operation is implemented for a microgrid composed of DERs on the supply side and HVAC with lighting on demand side. This energy management system EMS operates over a time horizon while satisfying some key constraints. The results show that the ED operation with a variable curve of utility grid will be more economic. Power generation from diesel is more economic during the on-peak time because the electricity price is $ 0.08 but the generation cost of power from diesel is about $ 0.06. The storage devices including batteries play a significant role in reducing the cost of energy because they can suitably operate renewable resources and the electricity prices. The thermal load power in both cases heating and cooling is achieved. The smart building is insulated very well, this means the resistance of the building shell has high value, thus the convective heat transfer through the building envelope will be low, and the relation between the thermal resistance of the building shell and the total cost is an inverse relationship. In further work, the model can be developed by considering other types of buildings and different energy storage devices.

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