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Author

Rafique, S, Nizami, MSH, Irshad, UB, Hossain, MJ, Town, GE

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# A customer-based-strategy to minimize the cost of energy consumption by optimal utilization of energy resources in an apartment building

S Rafique, MSH Nizami, UB Irshad, MJ Hossain and GE Town

School of Engineering, Macquarie University, Sydney, Australia

E-mail: [sohaib.rafique@gmail.com](mailto:sohaib.rafique@gmail.com)

**Abstract.** Global energy consumption in heating and cooling of buildings and in the transport sector together accounts for approximately two-thirds of total energy consumption. Consequently, it is important to maximize the use of renewable generation energy in these sectors, and to optimize the use of that energy by managing diverse sources and loads. This is particularly challenging in high-density residential premises where the space for such infrastructure is limited, and storage can have significant impact on energy utilization and demand. In this paper, we describe a customer-based strategy (CBS) to optimize the usage of the available energy resources in such scenarios. The effectiveness of the strategy was validated for an apartment block of 20 households with photovoltaic generation (PV) and stationary battery storage (BS) systems, each with a vehicle-to-grid (V2G) capable electric vehicle (EV). The modelling used real data for customer demand and included the cost of battery degradation and expected vehicle usage in optimizing resource scheduling. Substantial savings in energy costs were shown to be possible for each customer.

## Nomenclature

$n_t \in \{0, 1\}$  = energy purchase variable at 't'  
 $m_t \in \{0, 1\}$  = energy selling variable at 't'  
 $o_{t,h} \in \{0, 1\}$  = BS charging variable for 'h' at 't'  
 $s_{t,h} \in \{0, 1\}$  = BS discharging variable for 'h' at 't'  
 $u_{t,h} \in \{0, 1\}$  = EV charging variable for 'h' at 't'  
 $v_{t,h} \in \{0, 1\}$  = EV discharging variable for 'h' at 't'  
 $\lambda_t^+$  = cost of purchasing energy at 't' in cents/kWh  
 $\lambda_t^-$  = cost of selling energy at 't' in cents/kWh  
 $\theta^{deg}$  = cost of battery degradation in \$/Wh  
 $C_t^{B(deg)}$  = cost of BS capacity degradation at 't'  
 $C_t^{EV(deg)}$  = cost of EV capacity degradation at 't'  
 $\rho_{(c/d)}^B$  = charging/discharging power of BS in kW  
 $\rho_{(c/d)}^{EV}$  = charging/discharging power of EV in kW  
 $V^B$  = terminal voltage of BS in Volts  
 $V^{EV}$  = terminal voltage of EV battery in Volts  
 $\vartheta(\rho_{c/d})$  = battery capacity degradation

$E_t$  = net system energy at 't' in kWh  
 $E_t^{PV}$  = energy generated by PV at 't' in kWh  
 $E_{t,h}^H$  = energy consumption of 'h' at 't' in kWh  
 $E_{t,h}^{dt}$  = energy req. to travel by EV of 'h' at 't' in kWh  
 $\delta_{t,h}^B$  = SoC of BS of 'h' at 't' in (%)  
 $\delta_{t,h}^{EV}$  = SoC of EV of 'h' at 't' in (%)  
 $\delta_{t,h}^{DT}$  = SoC req. by EV of 'h' at 't' for travel in (%)  
 $\delta_{t,h}^{des}$  = desired SoC of EV of 'h' at 't' in (%)  
 $E_{max}^B$  = max energy capacity of BS in kWh  
 $E_{max}^{EV}$  = max energy capacity of EV in kWh  
 $E_t^{B(C)}$  = energy req. to charge BS at 't'  
 $E_t^{B(D)}$  = energy discharged by BS at 't'  
 $E_{t,h}^{EV(C)}$  = energy req. to charge EV of 'h' at 't'  
 $E_{t,h}^{EV(D)}$  = energy discharged by EV of 'h' at 't'  
 $\alpha_{t,h} \in \{0, 1\}$  = matrix of EV availability of 'h' at 't'

## 1. Introduction

Thermal management of buildings accounts for approximately 40% of global energy consumption and the transport sector is responsible for about 28% of energy consumption globally, the majority of



which is provided from carbon-based energy resources [1]. To minimize the cost of energy whilst also minimizing carbon-based energy usage requires an increase in the proportion of renewable energy generation and careful management of the diverse sources, loads, and storage in the two sectors. This is particularly challenging in high-density residential premises where the space for renewable energy generation infrastructure is very limited. With the advent of smart grid technology, Building Energy Management Systems can be designed to optimize the use of available energy resources against predefined criteria, e.g. to minimize cost, energy consumption, peak load, etc.

Electrification of the transport is expected over coming decades [2]. The relatively large batteries in electric vehicles (EVs) can be used to support the electricity grid, e.g. by provision of vehicle-to-grid (V2G) services [3]. For an apartment building with a limited number of solar PV panels, battery storage and the EVs, there should be an energy management system (EMS) to ensure optimal utilization of the available energy resources without compromising the needs of energy consumers (households and EV owners).

In this paper we propose a customer-based-strategy (CBS) to minimize the cost of energy consumption by optimal utilization of the available energy resources in an apartment building. The paper is organized as follows; Section II put this work in the context of other publications. Section III describes the methodology used in our work, and Section IV presents our analysis and results. Section V contains the summary and conclusion.

## 2. Literature Review

In this section we summarize research relevant to optimal utilization of PV, battery storage and EVs for buildings. Methods to minimize the cost of electricity in low density residential buildings containing some renewable energy generation and stationary storage were presented in [4]–[6]. The latter works did not consider the strong constraints on renewable generation capacity applicable in apartment buildings, nor did they consider charging and discharging of EVs.

In [7], authors examined the charging strategies of multiple (PHEVs) in an apartment building, equipped with a photovoltaic (PV) generation. In [8], the authors proposed a strategy to schedule the charge/discharge of EVs to reduce customer cost. In [9], [10], the authors proposed an EMS for apartment building with Vehicle-to-Home (V2H) systems. In [11], a Home Energy Management System (HEMS) using the battery of an EV/PHV. The latter works did not include fixed battery storage.

In [12], the authors proposed flexible vehicle-to-grid (V2G) coordination schemes for office buildings equipped with electric vehicle (EV) charging stations. In [13], the authors analyzed the impact of (PV) systems on battery storage and EVs in micro-grids. These works were based on non-residential buildings where energy consumption constraints and arrival/departures of vehicles are different compared to residential apartment building.

To the best of authors knowledge, to date no research has considered optimizing all possible energy resources in a single model while also considering battery capacity degradation and its associated cost; these are the key contributions of this paper.

## 3. Methodology

This section describes the developed strategy and the datasets used for validating the strategy. The optimization problem considers the household energy consumption, power generation from solar PV panels, charging/discharging of EV batteries for G2V-V2G operations, discharging of EV batteries for travel needs and charging/discharging of battery storage. The strategy also considers battery capacity degradation and its associated cost as a function of charging/discharging power for each charge/discharge cycle.

We have formulated the mathematical model of the existing system and simulated the model using real data. We compared the base case (BC) model with the proposed strategy. The objective function and constraint equations were developed and simulated on MATLAB/GAMS. Due to the non-linear nature of the objective function, we used a commercially available MINLP (mixed integer non-linear programming) solver (i.e. GAMS [14]) and analyzed the results in MATLAB.

### 3.1. Model details

#### 3.1.1. Base Case

The base-case model follows the ‘‘Greedy’’ algorithm. The algorithm works as follows;

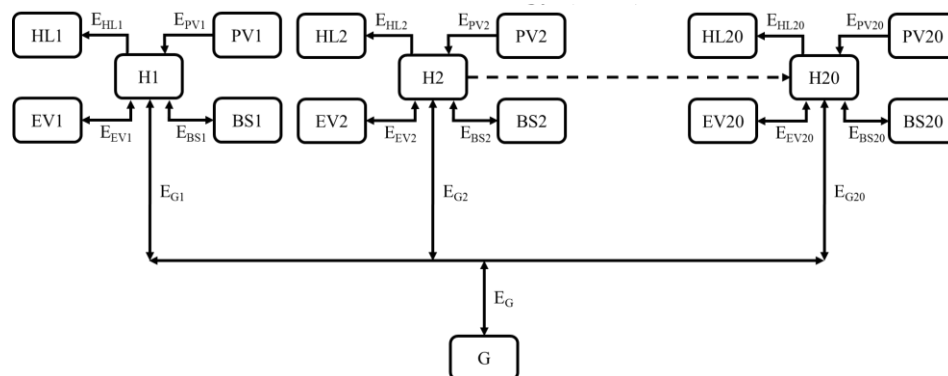
- EVs are charged as soon as they arrive home, without considering the energy tariff rates
- Discharging of EVs is not considered
- PV energy is utilized to charge the BS
- BS discharges during the peak hours

Greedy Algorithm for Base Case Model.

Base Case Pseudo Code	
If	'PV' is 'Available'
If	Tariff is 'Peak'
Then	Supply energy to the 'Load'
If	Tariff is 'Off-peak'
Then	Charge the 'BS' first
Then	Supply energy to the 'Load'
If	'PV' is 'Not-available'
Then	Supply the 'Load' first
Then	Charge the 'BS'

#### 3.1.2. Customer-based-strategy (CBS)

The CBS strategy is designed to minimize the cost of energy consumption for ‘individual household’ by optimal utilization of the available energy resources. Each household possess its own PV and BS along with EV as shown in **Figure 1**.



**Figure 1.** CBS energy flow model

#### 3.2. Assumptions:

- EV is plugged-in, whenever it arrives home
- Average energy consumption by an EV for distance travel is 0.16 kWh/km [16].
- SOC ( $\delta_{t,h}^{EV}$ ) for all EVs at the beginning of the day is 50% which is realistic as majority of the cars stay at home during night time and have enough time to recharge [16].
- Each EV should have the desired SoC before departure (19).

#### 3.3. Mathematical Modelling

The objective function (1) is the summation of electricity costs which is calculated by multiplying the net energy of the system ‘ $E_t$ ’, the decision variables ‘ $n_t$ ’ & ‘ $m_t$ ’, and the cost of energy purchase ‘ $\lambda_t^+$ ’ and cost of energy sold ‘ $\lambda_t^-$ ’ respectively.

$$Cost = \sum_{t=1}^T (n_t E_t \lambda_t^+ + m_t E_t \lambda_t^- + C_t^{B(deg)} + C_t^{EV(deg)}); \quad (1)$$

When ' $E_t$ ' is positive, ' $n = 1$  &  $m = 0$ ' the system 'purchase' energy from the grid. In other case, when the system has excess energy i.e. ' $E_t$ ' is negative, the system 'sell' energy to the grid. In each scenario there is a different time-of-use (TOU) tariff applied for sell/purchase of energy.

$$E_t = \sum_{h=1}^H (E_{t,h}^H + E_{t,h}^{EV(C)} \cdot u_{t,h} \cdot \alpha_{t,h} - E_{t,h}^{EV(D)} \cdot v_{t,h} \cdot \alpha_{t,h} + o_{t,h} \cdot E_{t,h}^{B(C)} - s_{t,h} \cdot E_{t,h}^{B(D)} - E_{t,h}^{PV}); \quad (2)$$

$$E_{t,h} = E_{t,h}^H + E_{t,h}^{EV(C)} \cdot u_{t,h} \cdot \alpha_{t,h} - E_{t,h}^{EV(D)} \cdot v_{t,h} \cdot \alpha_{t,h} + o_{t,h} \cdot E_{t,h}^{B(C)} - s_{t,h} \cdot E_{t,h}^{B(D)} - E_{t,h}^{PV}; \quad (3)$$

Equation (2, 3) represents the 'net energy' and 'energy exchange for individual household' respectively.  $+E_{t,h}$  is the energy purchased by house 'h' from grid at ' $\lambda_t^+$ ' (\$/kWh) and  $-E_{t,h}$  is the energy sold by house 'h' to the grid at ' $\lambda_t^-$ ' (\$/kWh).

$$n_{(t)} + m_{(t)} = 1; \quad (4)$$

$$n_{(t)} \cdot m_{(t)} = 0; \quad (5)$$

$$n_{(t)} \cdot E_{(t)} \geq 0; \quad (6)$$

$$m_{(t)} \cdot E_{(t)} \leq 0; \quad (7)$$

Equations (4, 5, 6, 7) represents the decision variables for energy sell/purchase.

$$s_{(t,h)} + o_{(t,h)} \leq 1; \quad (8)$$

$$s_{(t,h)} + o_{(t,h)} \geq 0; \quad (9)$$

$$u_{(t,h)} + v_{(t,h)} \leq 1; \quad (10)$$

$$u_{(t,h)} + v_{(t,h)} \geq 0; \quad (11)$$

Equations (8, 9) represents the decision variables for charging/discharging of stationary battery and (10, 11) represents the decision variables for charging/discharging of EV batteries for individual household.

$$\delta_{(t,h)}^B \geq \delta_{min}^B; \quad (12)$$

$$\delta_{(t,h)}^B \leq \delta_{max}^B; \quad (13)$$

$$\delta_{(t,h)}^{EV} \geq \delta_{min}^{EV}; \quad (14)$$

$$\delta_{(t,h)}^{EV} \leq \delta_{max}^{EV}; \quad (15)$$

Equations (12, 13, 14, 15) represents the upper and lower bounds of 'state of charge' for stationary battery and EV batteries respectively for individual household.

$$\delta_{t,h}^B = \delta_{(t-1,h)}^B + \frac{o_{t,h} E_{t,h}^{B(C)}}{E_h^{B(max)}} - \frac{s_{t,h} E_{t,h}^{B(D)}}{E_h^{B(max)}}; \quad (16)$$

Equation (16) represents the 'state of charge' of stationary battery for individual household.

$$\delta_{(t,h)}^{EV} = \delta_{(t-1,h)}^{EV} + \frac{E_{t,h}^{EV(C)} \cdot u_{t,h} \cdot \alpha_{t,h}}{E_h^{EV(max)}} - \frac{E_{t,h}^{EV(D)} \cdot v_{t,h} \cdot \alpha_{t,h}}{E_h^{EV(max)}}; \quad (17)$$

$$\delta_{(t,h)}^{EV} = \delta_{(t-1,h)}^{EV} - \frac{\alpha_{t,h} \cdot E_{t,h}^{dt}}{E_h^{EV(max)}}; \quad (18)$$

$$\delta_{(t,h)}^{EV} \geq \frac{\alpha_{t,h} \cdot E_{t,h}^{dt}}{E_h^{EV(max)}}; \quad (19)$$

Equations (17, 18, 19) represents the 'state of charge' of EV batteries for individual household.

$$\vartheta(\rho_{(c/d)}) = (\beta_1 V + \beta_3 V^2 + \beta_5 V^3 + \beta_7 V^4) + (\beta_2 + \beta_6 V) \cdot |\rho_{(c/d)}| + \frac{\beta_4}{V} \cdot |\rho_{(c/d)}|^2; \quad (20)$$

Equations (20) is the representation of battery degradation as function of charging/discharging power based upon [20].

$$C_t^{B(deg)} = \sum_{h=1}^H ((s_{(t,h)} + o_{(t,h)}) \cdot \vartheta(\rho_{(c/d)})^B \cdot \theta^{deg}); \quad (21)$$

$$C_t^{EV(deg)} = \sum_{h=1}^H ((u_{(t,h)} + v_{(t,h)}) \cdot \alpha_{t,h} \cdot \vartheta(\rho_{(c/d)})^{EV} \cdot \theta^{deg}); \quad (22)$$

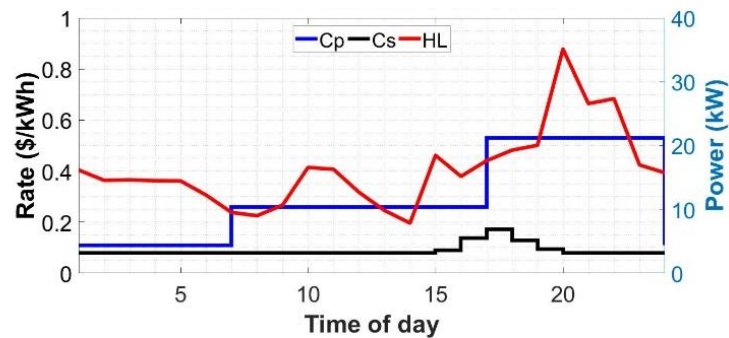
Equations (21, 22) represents the cost of battery capacity degradation for stationary battery and EV batteries respectively. Here, we have assumed the cost of battery degradation ' $\theta^{deg}$ ' to be 0.23 \$/Wh [21] for simulations.

### 3.4. Datasets

The details of the datasets used to validate the proposed model are presented below.

### 3.4.1. Apartment building load and tariff

Modelling was based upon actual electricity meter data and the time of use (TOU) tariff structure for a residential apartment building in Australia [15]. The building consists of five floors with four individual apartments on each floor and a ground floor with parking space. It is assumed that each apartment has its own designated parking space and a Level-1, bidirectional EV charger at 220 V, 15 A, 3 kW charging/discharging power with 10% losses, as used by [16], [17]. Each apartment has a floor surface of 92m<sup>2</sup>. Therefore, the roof has a total area of 369m<sup>2</sup>. Due to shading effects (e.g., tilted PV panels and other obstacles), the roof can only be partially covered with a perfectly oriented PV installation. This available surface has been set to 65% of the roof surface, i.e., 240m<sup>2</sup> [7].



**Figure 2.** Time of use (TOU) tariff and cumulative household load profile

### 3.4.2. PV System

The PV power production profile is synthetically generated using the tool described in [18]. Based on the manufacturer's data and the available roof area, the PV system for each household has a peak power of about 2.29 kW. The efficiency of DC-AC inverter is assumed to be 95% efficient. It is assumed that the panels are perfectly oriented to generate maximum annual electricity for the considered location as specified in [6]. For simulations we have used the specifications mentioned in **Table 1**.

**Table 1.** Specifications of Solar PV panels

Parameters	Specifications
Nominal Power ( $P_{NOM}$ )	327 W
Rated Voltage ( $V_{MPP}$ )	54.7 V
Rated Current ( $I_{MPP}$ )	5.98 A
Open-Circuit Voltage ( $V_{OC}$ )	64.9 V
Short-Circuit Current ( $I_{SC}$ )	6.46 A
Power Temp Coef.	-0.38% / °C
Voltage Temp Coef.	-176.6 mV / °C
Current Temp Coef.	3.5 mA / °C

### 3.4.3. Electric vehicles & travel data

Our simulations assumed that each household had one EV with a rated battery capacity of 24 kWh and a useful battery capacity of 19.2 kWh (i.e. 80% depth of discharge) as used by [16], [17]. Data for vehicle travel/usage pattern was extracted from The Victorian Integrated Survey of Travel and Activity (VISTA) [19]. Vehicles arrival/departure times and travel distances for all trips were extracted from VISTA data and the EV availability matrix for 20 households was developed **Figure 3**.

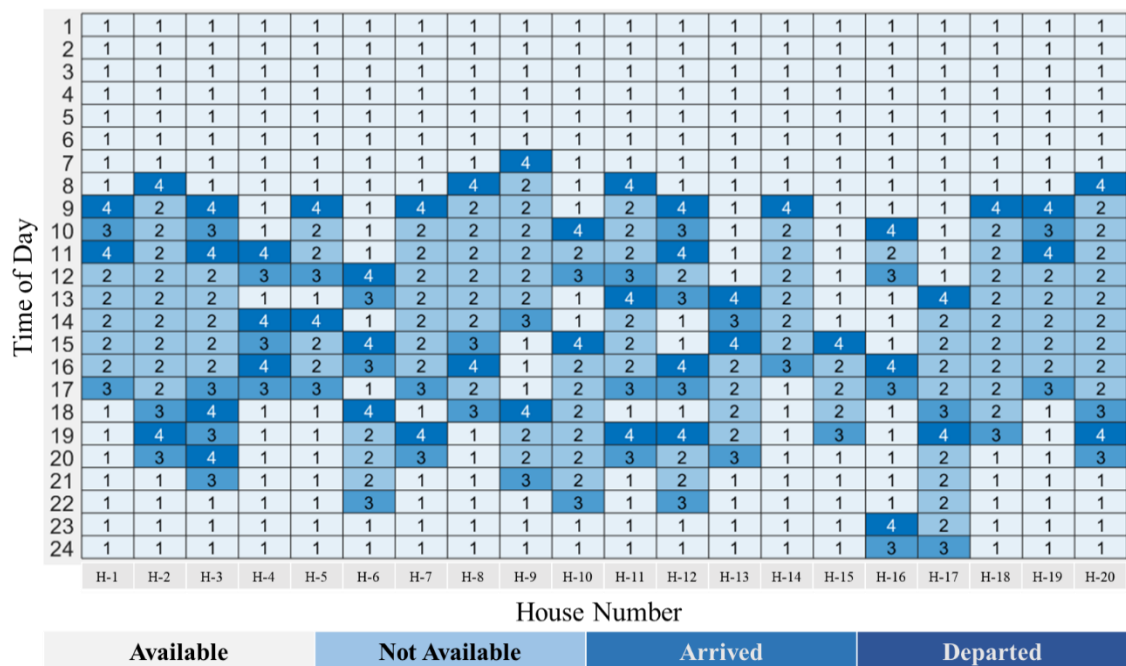


Figure 3. Electric vehicle (EV) availability matrix

3.4.4. Battery Storage

We assumed 20 BS modules (1 for each household), each with 14 kWh capacity and 5 kW charging/discharging power at 50 Hz, 230 VAC and 50 VDC (internal battery voltage).

4. Analysis & Results

The CBS utilizes the energy available from EV, PV and battery storage systems to minimize the cost of energy consumption for individual household in an apartment building. The graph plotted in Figure 4 shows the cumulative values of the power flow from different energy resources in the system for CBS. It shows that the net power drawn from the grid is considerably reduced in the CBS (i.e. Pg(CBS)), compared to the base case (i.e. Pg(BC)). The proposed CBS not only reduces the cost of energy consumption for the individual household but also reduces the net energy drawn from the grid.

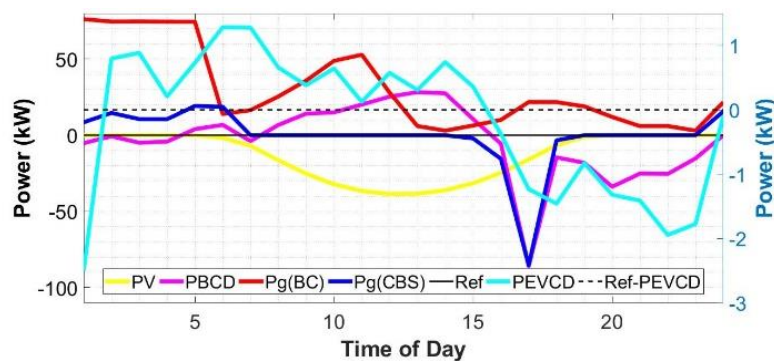


Figure 4. Comparison of power flows for CBS

Table 2 summarizes the results of CBS. The costs presented in Table 2 are the cumulative costs of energy consumption/production for 20 households. It is evident from cost figures that the cost of energy consumption for individual household has been reduced significantly compared to the non-optimal base case (BC).



**Table 2.** CBS Results Comparison with BC

Subsystem	CBS	BC	Difference
Household	-\$6.61	\$153.02	-\$159.63
PV	-\$28.29	-\$9.24	-\$19.05
BS	\$12.77	\$27.77	-\$15
EV	\$0.50	\$70.08	-\$69.58

A simple cost/benefit analysis was performed, and the results are tabulated in **Table 3**. Based on the cost of PV panels and battery storage from current market and assumptions regarding the system design and constraints outlined previously, the pay-back period for the CBS is evaluated to be approx. 4years. It should be noted that the pay-back period is less than the battery lifetime which is 10years.

**Table 3.** Cost/Benefit Analysis for the CBS

Parameters	CBS
Cost of unit PV panel	\$525
No. of PV panels installed	140
Total cost of PV panels	\$73,500
Cost of unit BS	\$8000
No. of BS units installed	20
Total cost of BS units	\$160,000
Estimated Daily Savings	-\$160
Estimated Yearly Savings	-\$58,263
Approx. Payback Period (Years)	4.0

## 5. Conclusion

Research has been conducted to optimize the utilization of available energy resources considering different combinations of consumers, producers and prosumers. However, the existing research have not addressed the optimal utilization of energy resources for a high-density building while also considering charging/discharging of EVs. The proposed methodology utilizes all possible available energy producers, consumers and prosumers, combined in a single model to minimize the cost of energy consumption for individual household in a high-density apartment building, while also considering the battery capacity degradation and its associated cost.

The results show that the proposed CBS is not only capable of reducing the cost of energy consumption for individual household but also significantly reduces the energy drawn from the grid by optimal utilization of the available energy resources. The cost benefit-analysis show that the pay-back period, for capital investment in PV panels and battery storage, is approximately 4 years, which is much less than the lifetime of the assets (battery storage and PV panels). The application of this strategy is not limited to the apartment buildings; for example, it could also be utilized for managing energy of a local micro-grid with residential/commercial buildings.

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