An aggregator-based-strategy to minimize the cost of energy consumption by optimal utilization of energy resources in an apartment building

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***Abstract*—Buildings and transport consume two thirds of the total global energy. It is desirable to maximize the use of renewable generation 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 have proposed an aggregator-based-strategy (ABS) to optimally utilize the available energy resources and storage in an apartment building with twenty households, each having an electric vehicle (EV), and an aggregated solar photo-voltaic (PV) energy and stationary battery storage (BS) system. The strategy is flexible and can be applied to any building with EVs, solar PV and BS to minimize the cost of energy consumption without compromising the flexibility of energy usage or travel requirements. The model also accounts for the battery capacity degradation and its associated cost to make it more realistic. The model is evaluated using real data and the results show that the strategy not only reduces the cost of energy consumption but also reduces the amount of energy drawn from the grid significantly.**

Keywords—optimization, electric vehicles, solar pv, battery storage, apartment building, aggregator, cost reduction, battery degradation

NOMENCLATURE

$n_t \in \{0,1\}$ = energy purchase at 't'
$m_t \in \{0,1\}$ = energy sell at 't'
$o_t \in \{0,1\}$ = Battery Storage (BS) charging at 't'
$s_t \in \{0,1\}$ = BS discharging at 't'
$u_{t,h} \in \{0,1\}$ = Electric Vehicle (EV) charging for 'h' at 't'
$v_{t,h} \in \{0,1\}$ = EV discharge for 'h' at 't'
λ_t^+ = cost of energy purchase at 't' (cents/kWh)
λ_t^- = cost of energy sell at 't' (cents/kWh)
θ^{deg} = battery degradation cost per charge/discharge (\$/Wh)
$C_t^{B(deg)}$ = BS capacity degradation cost at 't' due to charging/discharging
$C_t^{EV(deg)}$ = cumulative cost of EV battery capacity degradation at 't' due to charging/discharging
$\rho_{(c/d)}^{B}$ = charging/discharging power of BS (kW)
$\rho_{(c/d)}^{EV}$ = charging/discharging power of EV battery (kW)
V^B = terminal voltage of BS (volts)
V^{EV} = terminal voltage of EV battery in (volts)
$\vartheta(\rho_{c/d})$ = battery capacity degradation per charge/discharge
E_t = net system energy at 't' (kWh)
E_t^g = energy from/to grid at 't' (kWh)
E_t^{PV} = energy generated by solar photo-voltaic (PV) at 't' (kWh)
E_t^{ex} = energy exchange with household/EV at 't' (kWh)
$E_{t,h}^{H}$ = energy consumption of 'h' at 't' (kWh)
$E_{t,h}^{dt}$ = energy consumed due to distance travel by EV of 'h' at 't' (kWh)
δ_t^B = State-of-Charge (SoC) of BS at 't' (%)
$\delta_{t,h}^{EV}$ = SoC of EV battery of 'h' at 't' (%)
$\delta_{t,h}^{DT}$ = SoC required by EV of 'h' at 't' for travel needs (%)
$\delta_{t,h}^{des}$ = desired SoC of EV of 'h' at 't' (%)
E_{max}^{B} = max energy capacity of BS (kWh)
E_{max}^{EV} = max energy capacity of EV of 'h' (kWh)
$E_t^{B(C)}$ = energy required to charge BS at 't' (kWh)
$E_t^{B(D)}$ = energy discharged by BS at 't' (kWh)
$E_{t,h}^{EV(C)}$ = energy required to charge EV battery of 'h' at 't'
$E_{t,h}^{EV(D)}$ = energy discharged by EV battery of 'h' at 't'
$\alpha_{t,h} \in \{0,1\}$ = EV availability matrix for 'h' at 't'

Other variables, parameters, notations and abbreviations are described in the paper below.

I. 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 photo-voltaic (PV) panels, battery storage (BS) 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).

This paper is motivated by the challenges associated with the intermittent nature of the renewable energy resources and the opportunities presented by the uncertainties associated

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with EV usage. In this paper, we have proposed an aggregator-based-strategy (ABS) to minimize the cost of energy consumption for an aggregator, 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, Section IV presents our analysis and results. Section V discusses the practical applications of the proposed strategy. Section VI contains the summary and conclusion.

II. LITERATURE REVIEW

In this section we summarize research relevant to optimal utilization of solar 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 solar PV generation. In [8], the authors proposed a model 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) was presented 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 solar 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.

III. METHODOLOGY

This section describes the developed model and the datasets used for analysis. 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 model 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 proposed model with the base case (BC) model. The objective function and constraint equations were developed and simulated on MATLAB and 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.

A. Model details

1) Base Case: The base case model follows the “Greedy” algorithm. The algorithm works as follows;

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

GREEDY ALGORITHM FOR BASE CASE MODEL

Base Case Pseudo Code

```
If      'Solar 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      'Solar PV' is 'Not-available'
  Then    Supply the 'Load' first
  Then    Charge the 'BS'
```

2) Aggregator-based-strategy (ABS): The ABS is designed to minimize the cost of energy consumption for an ‘aggregator’, by optimal utilization of the available energy resources. It is assumed that the aggregator owns the solar PV and BS modules. Fig. 1 represents the energy exchange process flow for the ABS. The aggregator possesses an energy management system which is responsible for optimizing the utilization of available energy resources while considering associated constraints.

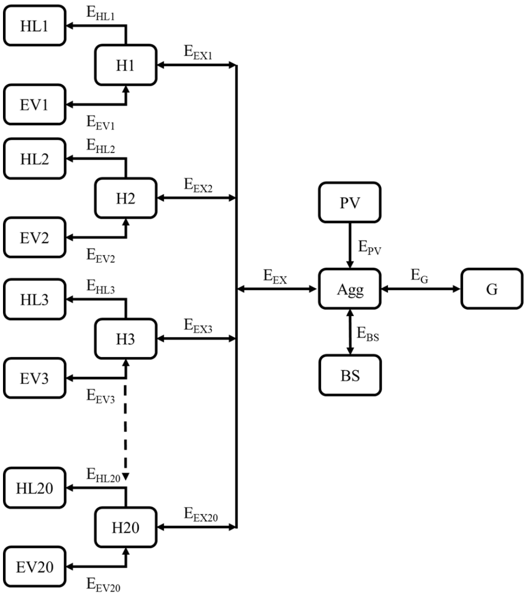


Fig. 1. Energy flow model for the ABS

3) Assumptions:

1. EV is plugged-in, whenever it arrives home
2. Average energy consumption by an EV for distance travel is 0.16 kWh/km [15].
3. 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 [15].
4. Each EV should have the desired SoC before departure (19).

B. 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 'λ_t^+' and cost of energy sold 'λ_t^-' respectively.

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

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.

$$E_t = E_t^g - E_t^{ex} \tag{2}$$

$$E_t^{ex} = \sum_{h=1}^{H} (E_{t,h}^{H} + E_{t,h}^{EV(C)} \, . \, u_{t,h} \, . \, \alpha_{t,h} - E_{t,h}^{EV(D)} \, . \, v_{t,h} \, . \, \alpha_{t,h}) \tag{3}$$

$$E_t^g + s_t \, . \, E_t^{B(D)} + E_t^{PV} = o_t \, . \, E_t^{B(C)} + E_t^{ex} \tag{4}$$

Here, 'E_t^g' is the energy exchange between the aggregator and the grid. 'E_t^{ex}' is the energy exchange between the aggregator and the houses. $+E_t^g$ is the energy purchased by the aggregator from grid and $-E_t^g$ is the energy sold by the aggregator to the grid. $+E_t^{ex}$ is the energy sold by the aggregator to the houses and $-E_t^{ex}$ is the energy purchased by the aggregator from the houses. Therefore, if the net energy 'E_t' is positive that means the aggregator has purchased energy at 'λ_t^+' and for this case '$n = 1 \,\&\, m = 0$'. In other case, when the net energy 'E_t' is negative, that means the aggregator has sold the energy to the grid at 'λ_t^-' (cost of selling energy) and for this case '$n = 0 \,\&\, m = 1$'.

$$n_{(t)} + m_{(t)} = 1 \tag{5}$$

$$n_{(t)} \, . \, m_{(t)} = 0 \tag{6}$$

$$n_{(t)} \, . \, E_{(t)} \geq 0 \tag{7}$$

$$m_{(t)} \, . \, E_{(t)} \leq 0 \tag{8}$$

Equations (5, 6, 7, 8) represent the buying/selling of energy constraints for the model.

$$s_{(t)} + o_{(t)} \leq 1 \tag{9}$$

$$s_{(t)} + o_{(t)} \geq 0 \tag{10}$$

$$u_{(t,h)} + v_{(t,h)} \leq 1 \tag{11}$$

$$u_{(t,h)} + v_{(t,h)} \geq 0 \tag{12}$$

Equations (9, 10) represent the decision variables for charging/discharging of stationary battery and (11, 12) represent the decision variables for charging/discharging of EV batteries.

$$\delta_{(t)}^{B} \geq \delta_{min}^{B} \tag{13}$$

$$\delta_{(t)}^{B} \leq \delta_{max}^{B} \tag{14}$$

$$\delta_{(t,h)}^{EV} \geq \delta_{min}^{EV} \tag{15}$$

$$\delta_{(t,h)}^{EV} \leq \delta_{max}^{EV} \tag{16}$$

Equations (13, 14, 15, 16) represent the upper and lower bounds of SoC for stationary battery and EV batteries respectively.

$$\delta_t^B = \delta_{(t-1)}^B + \frac{o_t E_t^{B(C)}}{E_{max}^B} - \frac{s_t E_t^{B(D)}}{E_{max}^B} \tag{17}$$

Equation (17) represents the SoC of stationary battery.

$$\delta_{(t,h)}^{EV} = \delta_{(t-1,h)}^{EV} + \frac{E_{t,h}^{EV(C)} \, . \, u_{t,h} \, . \, \alpha_{t,h}}{E_{max}^{EV}} - \frac{E_{t,h}^{EV(D)} \, . \, v_{t,h} \, . \, \alpha_{t,h}}{E_{max}^{EV}} \tag{18}$$

$$\delta_{(t,h)}^{EV} = \delta_{(t-1,h)}^{EV} - \frac{\alpha_{t,h} \, . \, E_{t,h}^{dt}}{E_{max}^{EV}} \tag{19}$$

$$\delta_{(t,h)}^{EV} \geq \frac{\alpha_{t,h} \, . \, E_{t,h}^{dt}}{E_{max}^{EV}} \tag{20}$$

Equations (18, 19, 20) represent the SoC of EV batteries for respective households.

$$\vartheta(\rho_{(c/d)}) = (\beta_1 V + \beta_3 V^2 + \beta_5 V^3 + \beta_7 V^4) + (\beta_2 + \beta_6 V) \, . \, |\rho_{(c/d)}| + \frac{\beta_4}{V} \, . \, |\rho_{(c/d)}|^2 \tag{21}$$

Equation (21) is the representation of battery degradation as function of charging/discharging power, inspired by [24].

$$C_t^{B(deg)} = (s_{(t)} + o_{(t)}) \, . \, \vartheta(\rho_{(c/d)})^{B} \, . \, \theta^{deg} \tag{22}$$

$$C_t^{EV(deg)} = \sum_{h=1}^{H} ((u_{(t,h)} + v_{(t,h)}) \, . \, \alpha_{t,h} \, . \, \vartheta(\rho_{(c/d)})^{EV} \, . \, \theta^{deg}) \tag{23}$$

Equations (22, 23) represent the cost of battery capacity degradation for stationary battery and EV batteries respectively. Here, we have assumed the cost of battery degradation 'θ^{deg}' to be 0.23 \$/Wh [16] for simulations.

C. Datasets

The proposed strategy is validated using real data. The details of the datasets are presented in the following subsections.

1) Apartment building load and tariff: Modelling was based upon actual electricity meter data and the time of use (TOU) tariff (Fig. 2) structure for a residential apartment building in Australia [17]. 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 [15], [18]. Each apartment has a floor surface of 92 m2. Therefore, the roof has a total area of 369 m2. Due to shading effects (e.g., tilted solar PV panels and other obstacles), the roof can only be partially covered with a perfectly oriented solar PV installation. This available surface has been set to 65% of the roof surface, i.e., 240 m2 [7].

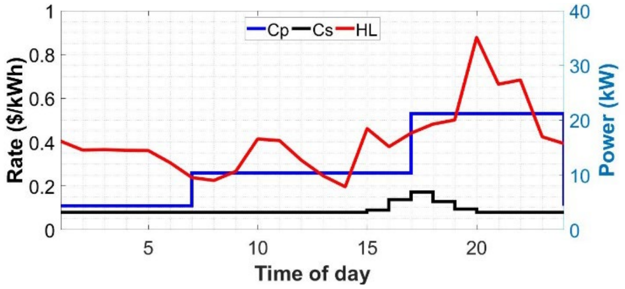


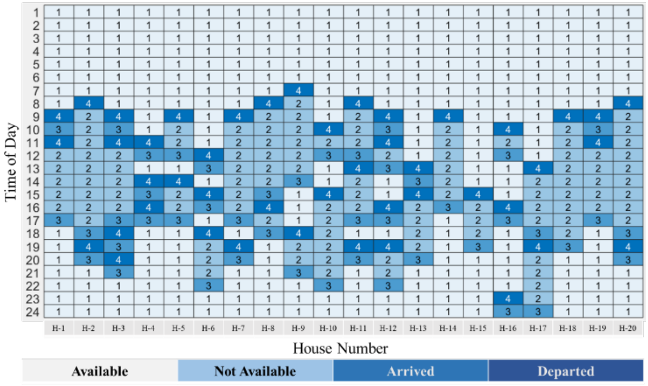
Fig. 2. Time of use (TOU) tariff and cumulative household load profile

2) Solar PV System: The solar PV power production profile is synthetically generated using the tool described in [19]. Based on the manufacturer's data and the available roof area, the solar PV system for the apartment block has a peak power of about 45.78 kWp. 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 I.

TABLE I. SPECIFICATIONS FOR SOLAR PV PANELS

Parameters	Specifications
Nominal Power (PNOM)	327 W
Rated Voltage (VMPP)	54.7 V
Rated Current (IMPP)	5.98 A
Open-Circuit Voltage (VOC)	64.9 V
Short-Circuit Current (ISC)	6.46 A
Power Temp Coef.	-0.38% / ºC
Voltage Temp Coef.	-176.6 mV / ºC
Current Temp Coef.	3.5 mA / ºC

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 [15], [18]. Data for vehicle travel/usage pattern was extracted from The Victorian Integrated Survey of Travel and Activity (VISTA) [20]. 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 Fig. 2.



Time of Day	H-1	H-2	H-3	H-4	H-5	H-6	H-7	H-8	H-9	H-10	H-11	H-12	H-13	H-14	H-15	H-16	H-17	H-18	H-19	H-20
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	4	1	1	1	1	1	1	1	1	1	1	1
8	1	4	1	1	1	1	1	4	2	1	4	1	1	1	1	1	1	1	1	4
9	4	2	4	1	4	1	4	2	2	1	2	4	1	4	1	1	1	4	4	2
10	3	2	3	1	2	1	2	2	2	4	2	3	1	2	1	4	1	2	3	2
11	4	2	4	4	2	1	2	2	2	2	2	4	1	2	1	2	1	2	4	2
12	2	2	2	3	3	4	2	2	2	3	3	2	1	2	1	3	1	2	2	2
13	2	2	2	1	1	3	2	2	2	1	4	3	4	2	1	1	4	2	2	2
14	2	2	2	4	4	1	2	2	3	1	2	1	3	2	1	1	2	2	2	2
15	2	2	2	3	2	4	2	3	1	4	2	1	4	2	4	1	2	2	2	2
16	2	2	2	4	2	3	2	4	1	2	2	4	2	3	2	4	2	2	2	2
17	3	2	3	3	3	1	3	2	1	2	3	3	2	1	2	3	2	2	3	2
18	1	3	4	1	1	4	1	3	4	2	1	1	2	1	2	1	3	2	1	3
19	1	4	3	1	1	2	4	1	2	2	4	4	2	1	3	1	4	3	1	4
20	1	3	4	1	1	2	3	1	2	2	3	2	3	1	1	1	2	1	1	3
21	1	1	3	1	1	2	1	1	3	2	1	2	1	1	1	1	2	1	1	1
22	1	1	1	1	1	3	1	1	1	3	1	3	1	1	1	1	2	1	1	1
23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	4	2	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	1	1	1

House Number

Available	Not Available	Arrived	Departed

Fig. 3. EV availability matrix

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

IV. ANALYSIS & RESULTS

Fig. 4. shows the power flow from different energy resources in the system for ABS. The net power drawn from the grid is considerably reduced in the ABS (i.e. Pg-ABS), compared to the BC (i.e. Pg-BC). The proposed ABS not only reduces the cost of energy consumption for the system but also reduces the load on grid. The ABS also utilizes the available solar PV and BS energy systems to minimize the overall cost for the aggregator.

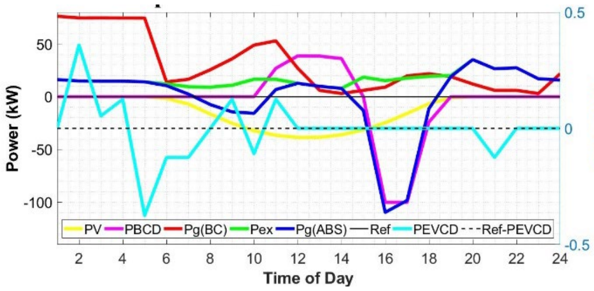


Fig. 4. Comparison of power flows using the ABS

The results of ABS are summarized in Table II. It is clear from the cost figures that ABS significantly reduces the cost of energy consumption for the aggregator compared to the un-optimized base-case (BC). The cost of energy consumption for individual household is also reduced as a result of overall system cost optimization.

TABLE II. ABS COMPARISON WITH BASE-CASE

Parameters	ABS	BC	Diff
Aggregator	-$51.25	$151.27	-$202.52
Household	$130.34	$200.47	-$70.14
PV	-$28.30	-$9.86	-$18.44
BS	-$22.96	$27.77	-$50.73
EV	$0.09	$70.08	-$69.99

A simple cost/benefit analysis was performed and the results are tabulated in Table III. The payback period for the initial investment on solar PV and BS is approximately 3years.

TABLE III. COST-BENEFIT ANALYSIS FOR ABS

PARAMETERS	ABS
Cost of unit PV panel [21]	$525
No. of PV panels installed	140
Total cost of PV panels	$73,500
Cost of unit BS [22]	$8000
No. of BS units installed	20
Total cost of BS units	$160,000
Estimated Daily Savings	-$203
Estimated Yearly Savings	-$73,922
Approx. Payback Period (Years)	3.2

V. APPLICATIONS

This paper presents the numerical validation of the proposed aggregator based strategy (ABS) to minimize the cost of energy consumption by optimal utilization of the available energy resources for an apartment building. However, this strategy is equally applicable to an aggregator of microgrids with a mix of residential and commercial buildings to achieve the following objectives;

1. minimizing cost of energy consumption
2. minimizing the energy drawn from the grid

VI. CONCLUSION

In this work we have developed a model and strategy to determine the optimal utilization of energy resources available in a high density apartment, including the use of electric vehicles for energy management and transport. The proposed methodology utilizes all possible available energy producers, consumers and prosumers, combined in a single system to minimize the cost of energy consumption, taking into account time of use tariffs for individual households in a high-density apartment building, whilst also considering typical electric vehicle transport needs, and battery capacity degradation and associated costs.

The results show that the proposed ABS is not only capable of reducing the cost of energy consumption for the aggregator 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 solar PV panels and battery storage is approximately 3 years, which is much less than the lifetime of the assets (battery storage and solar PV panels).

The scalability of the proposed strategy makes it adaptable for a larger network with higher penetration level of EVs. The proposed strategy will be evaluated with diverse EV usage data and larger network in the future researches by the authors. Future researches will also focus on the detailed cost-benefit-analysis and pay-back period considering all costs involved, which was not considered in this paper.

VII. ACKNOWLEDGMENT

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