A Reward Mechanism for Reliability-as-a-Service Usage of Electric Vehicles

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***Abstract*—Instead of using a dedicated backup power source to fulfill the energy needs of buildings during contingencies, a reward mechanism for providing reliability-as-a-service (RaaS) via electric vehicles (EVs) is proposed in this study. The proposed positive reward mechanism comprises an upfront reward portion (paid upon registering) and a per-event reward portion (paid based on the amount of energy used). Similarly, a negative reward is applied to the registered EV owners not complying with their contracts. In addition, a score updating mechanism is proposed to incentivize EVs following their contracts and penalize the violating EVs. The score will be decisive during events when more EVs are available than the required energy. The use of EVs for providing RaaS is compared with two commonly used technologies for backup power, i.e., diesel generator and battery storage. Simulations have shown that the proposed scheme can significantly save the cost for building operators/owners while providing revenues for EV owners. The fairness in incentive allocation versus the amount of used energy is also demonstrated.**

Keywords—backup power, electric vehicles, power contingency, reliability-as-a-service (RaaS), reward mechanism.

I. INTRODUCTION

Due to the reduction in the cost of batteries, concerns over climate change, and subsidies provided by governments, transportation electrification has gained momentum across the globe [1]. It has been estimated by International Energy Agency (IEA) that the size of the global EV fleet will reach 140-245 million by 2030 [2]. Similarly, the useable battery size of electric vehicles (EVs) is also increasing, i.e., the average battery size of commercially available EVs (as of August 2021) is about 60kWh [3]. According to the U.S. National Household Travel Survey (NHTS) data, most of the vehicle owners drive under 100km in a day [4] while the average energy consumption of commercially available EVs, to date, is about 0.2kW/km [3]. It implies that on average, each fully charged EV has excess energy of about 40kWh.

Meanwhile, backup generators are commonly installed in buildings to feed the local loads during system contingencies. A study has shown that diesel generators are the most common type of backup generators used in Canada, due to the higher energy density and lower maintenance cost [5]. The use of renewable technologies for providing backup power has also been assessed and energy storage is suggested as a viable option [5]. However, the frequency of contingencies is low, i.e., about 9-hours per year [6], while the backup resources need to be installed and maintained (throughout the year). This increases the cost for the building owners, especially for commercial and industrial buildings. Instead of dedicated backup power resources, EVs can be used to provide power to buildings during contingencies, i.e., reliability-as-a-service (RaaS) usage of EVs.

To realize the RaaS feature of EVs, the vehicle-to-grid (V2G) technology is required. It is currently in the commercialization phase [7], and several tests have been conducted for different applications. For example, a microgrid case in the USA [8], frequency regulation in Norway [8], or market participation in the UK [9]. Similarly, several studies have been conducted to assess the potential benefits of V2G services. Economic analysis of various V2G services considering market prices and battery degradation is presented in [10] and analysis of wind power coupled V2G services is shown in [11]. Benefits of V2G for peak shaving [12], frequency regulation via a fleet of school busses [13], and benefits of active/reactive power support for distribution systems [14] are analyzed in these studies. However, all these services are frequently required and can increase the battery degradation of EVs. It has been reported in [10] that the two major factors influencing the decision of EV owners to participate in V2G services are financial compensation (incentives) and battery degradation.

RaaS is a potential application of EVs, that has been little explored in the existing literature. EVs can be used during reliability-oriented events, where the contingency duration is typically under a few hours [15]. In addition, these events are localized and are small-scale contingencies. This could be of special interest for mixed buildings (residential and commercial) with shared parking lots. The probability of the presence of EVs at all times is higher in such a nexus, increasing the service reliability of both types of buildings during contingencies. Due to the low occurrence of power contingency events, EVs are not required to participate frequently in RaaS. Similarly, EV owners can contract a specific amount of energy per event/per year considering their daily traveling mileage, battery capacity, and depth of discharge. These considerations along with the less frequent triggering of RaaS events will reduce battery degradation. In addition, the presence of EVs in a location (e.g., apartment, school, university, etc.) correlates with the presence of humans, which implies that higher amount of energy will be required during contingencies and vice versa. Therefore, the use of EVs in providing RaaS is a practical application of V2G. However, designing a reward mechanism for EV is a non-trivial task. The reward mechanism should provide ample incentives for EV owners to participate in and comply with RaaS programs while making it profitable for the building operators.

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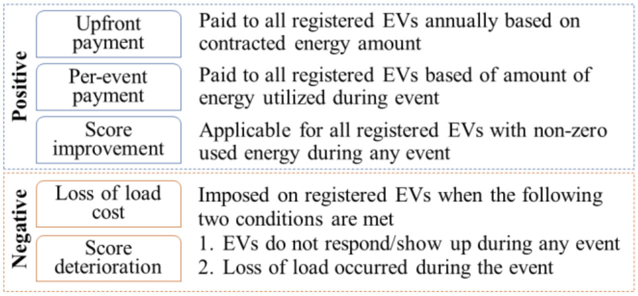

Fig. 1. The proposed reward mechanism for EV owners.

To facilitate the use of EVs for providing RaaS during contingencies, a reward mechanism is proposed in this study. The reward mechanism comprises two monetary incentives and a score improvement factor. The monetary incentives are composed of an upfront portion, paid upon registering in the RaaS program, and a per-event portion, paid to participating EV owners based on the amount of energy being used. Negative rewards are applied to registered EVs that do not show up during a triggered event which resulted in the loss of load. The score improvement is to incentivize the EVs to comply with their contracts and score deterioration is for penalizing EVs which violate the contract. If the amount of required energy is smaller than the available energy (EVs), EVs with higher scores will be preferred, which will increase their revenue. The use of EVs as a RaaS is compared with two commonly used backup power sources (diesel generator and BESS) and the yearly savings of building owners along with the revenue of EV owners is computed. Finally, the fairness of the proposed mechanism in terms of allocation of incentives against the amount of energy being used from EVs is also analyzed.

II. REWARD MECHANISM

A. *Reward Allocation Mechanism*

To tempt the EV owners to register for providing RaaS and comply with their contracts, this study proposes a reward mechanism, shown in Fig. 1. The reward mechanism comprises a three-step positive and a two-step negative factors. The upfront payment is paid to each registered EV owner irrespective of the number of triggered events. The per-event payment is paid only to EV owners who participated in any triggered event and the owners may face negative rewards if they did not show up during an event and it resulted in the loss of load. Each EV is assigned a score based on the past response history of the EV owner and it will be useful to select EVs if more are available during an event (compared to the required energy amount).

B. *Revenue Calculation*

To calculate the yearly revenue for EV owners, a mechanism is proposed in this study. In addition, to compare the cost/ savings of the building owner/operators, two commonly used technologies are considered in this study, which are diesel generators and battery energy storage system (BESS). The step-by-step revenue calculation process is shown in Fig. 2.

1) Annualized cost of alternative technologies: First, the cost of different components of the alternative technologies are collected. Then, the annualized cost for BESS (C^{bess}) is computed as follows:

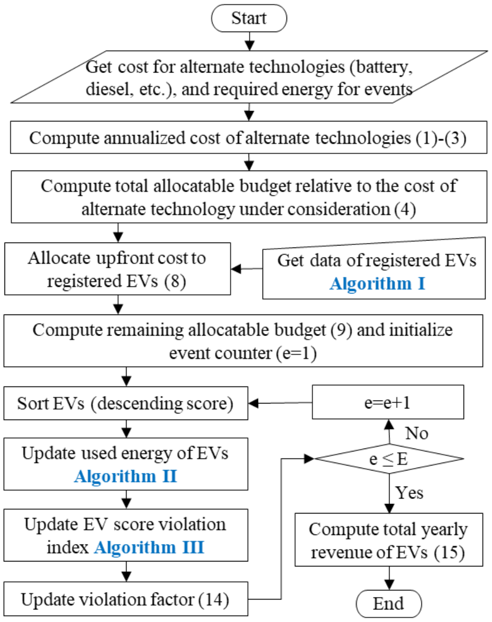

Fig. 2. The proposed revenue calculation process.

$$C^{bess} = \left(C^{pcs} + C^{b} + C^{bop}\right).\gamma + C^{onm}. \tag{1}$$

where C^{pcs} , C^{b} , C^{bop} , and C^{onm} are the costs for power conversion system, battery, the balance of plant, and operation & maintenance (yearly), respectively. Similarly, the annualized cost of diesel generator (C^{die}) is computed as follows:

$$C^{die} = C^{cap}\cdot\gamma + C^{m} + C^{pm} + C^{fuel}. \tag{2}$$

where, C^{cap} is the capital cost while C^{m}, C^{pm}, C^{fuel} are the annual maintenance, preventive maintenance, and fuel costs, respectively. In both equations, capital recovery factor (γ) is used to convert the total cost to yearly cost using the interest rate (i_r) and the equipment life in years (y), as follows:

$$\gamma = i_r.(1+i_r)^{y} \big/ ((1+i_r)^{y} - 1). \tag{3}$$

Then, the building operators can determine the maximum amount of budget to be allocated (C^{tot}) for the RaaS, considering the cost of available alternate technologies (C^{alt})

$$C^{tot} = C^{alt}\cdot(1-\delta), \tag{4}$$

where, δ is the minimum profit factor in the range of [0,1].

2) EV useable energy calculation: Each EV owner determines the contractable power according to Algorithm I and sends it to the building operator. First, the amount of required energy for the daily commute (E_n^{req}) is determined using the daily mileage (D_n) and the efficiency of the EV (η_n)

$$E_n^{req} = D_n\cdot\eta_n. \tag{5}$$

The algorithm I EV data reporting.

```
Determine daily average distance covered
Determine energy required to cover the distance (5)
Determine useable energy (6) and decide contract amount
Inform the operator about the contract amount in kWh
for all $e \in E$ do
    Receive event signal from the operator
    Inform the operator about the availability ($A_n$)
end for
```

The useable energy (E_n^{use}) amount can be computed using the capacity of the battery ($E_n^{\max}$), depth of discharging factor (λ_n^{mar}), and required amount of energy for the daily commute (E_n^{req})

$$E_n^{use} = E_n^{\max} - E_n^{\max} \cdot \lambda_n^{mar} - E_n^{req}. \tag{6}$$

The contracted amount cannot be greater than the useable energy amount, as depicted below:

$$E_n^{con} \le E_n^{use}. \tag{7}$$

After gathering information from all EV owners, the building operator allocates the upfront incentive (C_n^{uf}) based on the contracted amount (E_n^{con}) and the per-unit price (π^{pu})

$$C_n^{uf} = E_n^{con} \cdot \pi^{pu}. \tag{8}$$

Then, the remaining budget (C^{rem}), to be allocated on the per-event basis, is computed using the following equation

$$C^{rem} = C^{tot} - \sum_{n \in N} C_n^{uf}. \tag{9}$$

3) Event-wise used energy calculation: All registered EVs are sorted based on their score and the amount of energy used from each EV, during any event, is updated using Algorithm II. The required energy amount for the event is determined first and the acquired energy (E_e^{acc}) amount is updated starting from the EV with the highest score. If the amount of acquired energy is smaller than the required energy amount, the amount of energy used from the n^{th} EV is computed as

$$E_{n,e}^{used} = E_n^{con} \cdot A_n, \tag{10}$$

where, A_n is the availability indicator for nth EV. Otherwise, the used energy amount from the n^{th} EV is determined considering the remaining required energy amount for event *e*

$$E_{n,e}^{used} = \max\left\{\left(E_e^{req} - E_e^{acc} + E_n^{con}\right), 0\right\}. \tag{11}$$

4) EV score updating: The score of EVs is updated after each event to incentivize EVs participating in the event and penalize those not complying with their contracts. The EV score will play a significant role during those events where the available energy amount (number of EVs) is higher than the required energy amount. The score update process is outlined in Algorithm III, score (S_n) of EVs providing RaaS during any event is updated as follows:

$$S_n = S_n + \alpha \cdot A_n \tag{12}$$

where α is the incentive factor. Similarly, the score of EVs not complying with their contracts is updated as follows:

$$S_n = S_n - \beta \cdot (1 - A_n), \tag{13}$$

where β is the negative reward factor. To penalize the EVs not showing up during any event, violation factor ($V_{n,e}^{fac}$) is computed relative to the violation (V_n) of other EVs and the amount of lost load

$$V_{n,e}^{fac} = V_n \cdot \left(E_e^{req} - \sum_{n \in N} E_n^{used}\right) \Big/ \sum_{n \in N} V_n, \tag{14}$$

where, $V_n = V_n + (1 - A_n) \cdot E_n^{con}$.

Algorithm II Updating used energy of EVs during event *e*.

```
Initialize acquired energy: $E_e^{acc} = 0$
Get required energy for event e ($E_e^{req}$)
for all $n \in N$ do // Accessing the sorted array
    Update acquired energy: $E_e^{acc} += E_n^{con}$(contracted amount)
    if $E_e^{acc} < E_e^{req}$ do
        Update energy used ($E_{n,e}^{used}$) from $n^{th}$ EV using (10)
    else
        Update energy used ($E_{n,e}^{used}$) from $n^{th}$ EV using (11)
    end if
end for
```

Algorithm III Updating score of EVs after each event.

```
Get energy used from EVs $E_{n,e}^{used}$ and initialize $V_n$ to 0
Compute total energy used: $E_e^{tot} = \sum_{n \in N} E_{n,e}^{used}$
for all $n \in N$ do
    if $E_{n,e}^{used} > 0$ do
        Update EV score ($S_n$) of $n^{th}$ EV using (12)
    end if
end for
if $E_e^{tot} < E_e^{req}$ do
    for all $n \in N$ do
        Update EV score ($S_n$) of $n^{th}$ EV using (13)
        Update violation index ($V_n$) using (14)
    end for
end if
```

5) Yearly revenue calculation: The total yearly revenue for each EV can be computed by considering the up-front payment and the per-event incentives paid throughout the year. In addition, negative rewards imposed on EVs for not complying with the contract are subtracted from the revenue as follows:

$$C_n^{tot} = C_n^{uf} + C^{pu} \cdot \sum_{e \in E}\left(E_{n,e}^{used} - \vartheta \cdot V_{n,e}^{fac}\right), \tag{15}$$

where, $C^{pu} = C^{rem} \Big/ \sum_{n \in N} \sum_{e \in E} E_{n,e}^{used}$.

where ϑ is the negative reward factor for per unit of the lost load and C^{pu} is the worst-case (maximum number of events) per-unit incentive price for the on-event phase.

III. SIMULATION RESULTS

A. Input Data*

The performance of the proposed reward mechanism is tested for a building complex with a peak load of 300kWh and a total of 12 events are considered for a year. The duration of the 12 events is taken as [1,3,2,4,4,3,2,2,1,4,1,3] hours. The parameters of the two alternative technologies (BESS and diesel) are shown in Table I. The cost parameters of the battery are taken from [16] while the balance of plant (BOP), annual operation and maintenance (O&M), and power conversion system costs are taken from [17]. The depth of discharge is taken as 85% while the round-trip efficiency is 90%, like [17]. The cost for a diesel generator of 300kW (peak load) is computed using the Cost of Ownership computing tool [18]. The obtained results for yearly fuel cost, preventive maintenance (PM) cost, fuel maintenance (FM) cost, and load bank cost are tabulated in Table I. The initial fuel cost and the capital cost turned out to be 202,389$ and 5.63$, respectively. It has been reported in [19] that the daily mileage in the greater Edmonton region has a mean (μ) of 41.1km with a standard deviation (σ) of 14.6km. The distance for each EV owner is randomly generated in the range of μ±σ. The size of batteries is randomly generated between 30-120kWh based on the data

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*All costs are in CAD ($) [1USD is taken as 1.2CAD]

TABLE I. BESS AND DIESEL GENERATOR COST PARAMETERS.

BESS			Diesel generator		
Parameter	Value	Unit	Parameter	Value	Unit
Battery	164	$/kWh	Fuel	3607	$/yr
BOP	59	$/kWh	PM	3030	$/yr
O&M	20	$/kWh/yr	FM	612	$/yr
PCS	84	$/kW	Load bank	2599	$/yr

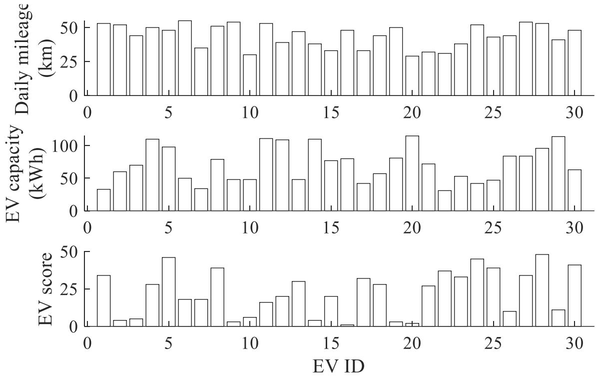


Fig. 3 EV-wise daily mileage, battery capacity, and score data used in simulations.

of the commercial EV database [3] and the average mileage is taken as 0.195kWh/km [3]. The EV-wise data used for simulations is shown in Fig. 3. The cost of electricity in the Edmonton region is 0.32$/kWh.

B. *Comparison with Alternative Technologies*

In this section, two extreme cases of events (no event and the maximum number of events) are considered to analyze the cost-saving for building operators and incentives for EVs. In all other cases, the incentive and cost values will be in between these two bounds. It is assumed that for both alternative technologies, operators are willing to pay up to 90% (δ=0.1) for EVs as incentives, i.e., minimum profit is 10%.

It can be observed from Fig. 4 that building operators can save a significant amount of cost under the no event case for using EVs to provide RaaS. Similarly, under the maximum number of events case, building operators were able to save up to 10% of the cost. In the no event case, EVs have received the upfront incentive for merely registering for the RaaS program. However, the incentive for EVs has significantly increased under the maximum number of events case. The EV-wise incentive allocations are shown in Figs. 5 and 6. The amount of energy used from EVs during 12 events is shown in Fig. 7, where the circles represent the average energy amount. It can be observed from Fig. 7 that EVs with higher scores are used frequently and can get higher incentives. For example, EV 5 and 28 are used for all 12 events and their incentives are the highest (Fig. 5 and 6). Contrarily, EV 16 is selected for 3 out of 12 events (the lowest score EV) and thus the incentive is the lowest.

C. *Evaluation of the Proposed Reward Mechanism*

1) Fairness of incentive allocation: The input data described in Section III-A is used in this section. After the end of each event, scores are updated based on the response of EV owners. However, for the first event, the score data of the previous year is required. Therefore, scores are randomly generated in the range of [1, 50] for the first event, as shown in Fig. 3. The initial score of EVs registering for the first time can be determined based on the amount of contracted energy amount. The scores are especially important for those events where the required energy is smaller than the total energy available in the EVs, i.e., few EVs need to be selected. Event-wise EV score updating results are shown in Fig. 8, where white boxes represent positive scores and red boxes represent zero scores. It can be observed from Fig. 8 that EVs with top scores (1, 5, 8, 22, 24, 25, 27, 28, 30) are used for all 12 events. Similarly, EVs with low scores (2, 3, 9, 14, 16, 19, 20) are used during only three events (4, 5, 10), when energy demand is higher. Fig. 9 shows a linear relationship between the amount of energy being used and the incentive received by EVs in a year, where the total incentive is the sum of the event and upfront incentives. The graph shows that the total incentive amount increases in proportion to the amount of energy used, throughout the year.

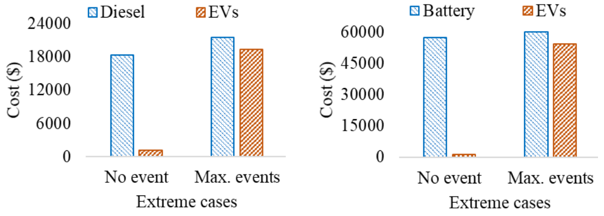


Fig. 4 Cost comparison of EVs and alternative technologies under extreme cases.

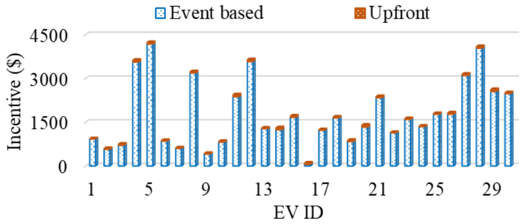


Fig. 5 Incentive allocation considering BESS as alternative.

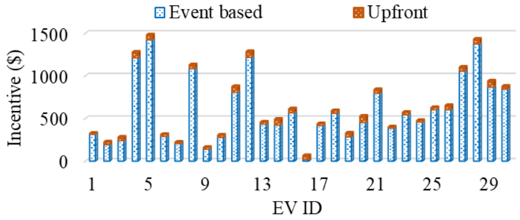


Fig. 6 Incentive allocation considering diesel as alternative.

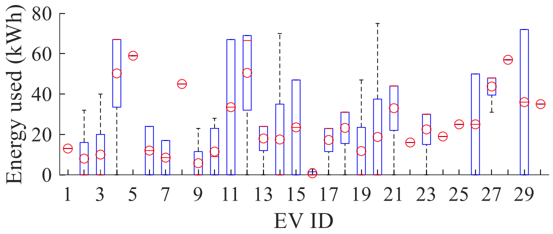


Fig. 7 Energy used from different EVs during events.

2) Negative reward allocation analysis: To evaluate the performance of the proposed reward mechanism under load loss conditions, the worst-case scenario needs to be simulated. Therefore, two of the highest load events (E4, E5) are selected. In addition, it is assumed that 5 EVs (26-30), with relatively high contracted energy, have not shown up during these two

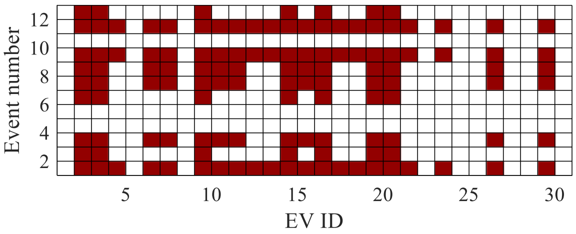


Fig. 8 EV-wise score updating during events.

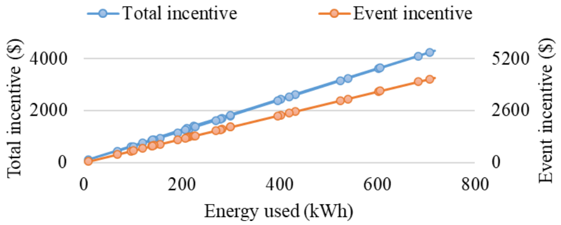
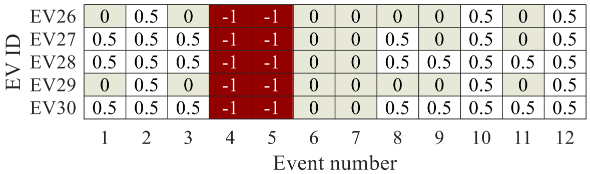


Fig. 9 Yearly used energy versus allocated incentives.



EV ID	1	2	3	4	5	6	7	8	9	10	11	12
EV26	0	0.5	0	-1	-1	0	0	0	0	0.5	0	0.5
EV27	0.5	0.5	0.5	-1	-1	0	0	0.5	0	0.5	0	0.5
EV28	0.5	0.5	0.5	-1	-1	0	0	0.5	0.5	0.5	0.5	0.5
EV29	0	0.5	0	-1	-1	0	0	0	0	0.5	0	0.5
EV30	0.5	0.5	0.5	-1	-1	0	0	0.5	0.5	0.5	0.5	0.5

Fig. 10 Score updating of EVs under load loss.

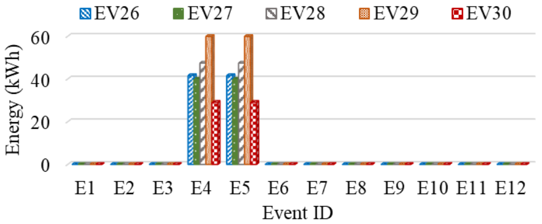


Fig. 11 Lost load allocation among contract violating EVs.

events. Due to higher energy demand (4*300 kWh), 218 kWh of the load is lost during both events. Fig. 10 shows that the score of these 5 EVs was reduced during those two events while it was increased for the remaining participated events. Similarly, the lost load is proportionally (based on the contracted amount) divided among the five EVs using (14), as shown in Fig. 11. Based on the allocated lost load amount, EVs are penalized for violating the contract and the net revenue is reduced, as shown in (15).

IV. CONCLUSION

A reward mechanism for using electric vehicles to provide reliability-as-a-service during power contingencies in buildings is proposed in this study. The reward mechanism comprises monetary and intangible positive/negative rewards to tempt electric vehicle owners to register and comply with their contracts. An algorithm is developed to calculate the yearly revenues of electric vehicle owners based on the contracted and actual amount of energy used. It has been demonstrated that the proposed mechanism can significantly reduce the cost for building operators, especially during no events or for small number of events. In addition, it can generate additional revenue for electric vehicle owners without disturbing their daily activities. Finally, the proposed mechanism can fairly allocate the incentives among different electric vehicles based on the amount of energy used during different events.

The focus of this study is on the one-to-one comparison of different technologies. However, consideration of mixed technologies, such as the integration of renewables with all these three options (diesel, BESS, and EVs) would be an interesting extension to this study. This is an initial financial feasibility study on using EVs for providing RaaS during reliability-oriented events. The authors are planning to carry out follow-up research considering the stochasticity of EVs along with power flow analysis of the connected system in the near future.

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