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Economic Viability Assessment of Repurposed EV Batteries Participating in Frequency Regulation and Energy Markets

Sarah Robson
Dept.of Engineering
Smith College
Northampton, USA
srobson@smith.edu

Abdullah M Alharbi
Dept.of Engineering
Sattam Bin Abdulaziz University
University of Denver
Al Karhj, KSA
abdullah.alharbi@du.edu

Wenzhong Gao, Amin Khodaei
Dept.of Electrical Engineering
University of Denver
Denver,USA
david.gao@du.edu
amin.khodaei@du.edu

Ibrahim Alsaidan
College of Engineering
Dept. of Electrical Engineering
Qassim University
Buraidah, KSA
alsaidan@qec.edu.sa

***Abstract*—The high cost and growing environmental concerns surrounding lithium-ion batteries have motivated research into extending the life of electric vehicle (EV) batteries by repurposing them for second life grid applications. The incorporation of repurposed electric vehicle batteries (REVBs) has the potential to decrease the overall cost of new battery energy storage systems (BESS) and extend the useful life of the materials. This paper focuses on maximizing daily profit that can be made from REVBs by stacking two grid services such as frequency regulation and energy arbitrage while minimizing battery capital cost by using second life EV batteries. A model for battery management with stacked frequency regulation and energy arbitrage is developed and tested using PJM market data. A mixed integer linear programming (MILP) is used to solve the optimization problem. It is found that REVBs can generate higher net profits than a new BESS.**

***Index Terms*—repurposed electric vehicle batteries, second life electric vehicle batteries, frequency regulation, arbitrage, stacked revenue services, battery management, lithium-ion batteries, ancillary services.**

NOMENCLATURE

Sets and Indices

d	Index of days
t	Index of hours

Parameters

λ	Discharging/charging efficiency of battery
B^{ER}	Battery energy rating (MWh)
B^{PR}	Battery power rating (MW)
$C_{100\%}$	Cycle life to reach 80% original capacity at 100% DoD
C_{DoD}	Cycle life to reach 80% original capacity at the given DoD
C_{max}	Maximum number of cycles that can be performed during the time period
D_{dt}^{down}	Ramp down signal from regulation market
D_{dt}^{up}	Ramp up signal from regulation market
DoD	Depth of discharge
lmp_{dt}	Real time electricity price ($/MWh)
M_{dt}	Mileage ratio
R_{dt}^{MCCP}	Hourly Regulation Market Capability Clearing Price ($/MWh)
R_{dt}^{MPCP}	Hourly Regulation Market Performance Clearing Price ($/MWh)
S_{dt}	Performance score of the batteries system

Variables

A_{dt}^{b}	Power bought from the energy market (MW)
A_{dt}^{s}	Power sold to the energy market (MW)
Arb_r	Revenue from participating in energy market
C	Number of cycles performed by the batteries system
$F_{A,dt}^{down}$	Actual power supplied for regulation ramp down (MW)
$F_{A,dt}^{up}$	Actual power supplied for regulation ramp up (MW)
$F_{bid,dt}$	Total capacity available for biding in the frequency regulation market (MW)
F_{dt}^{down}	Ramp down (charging) regulation bid (MW)
F_{dt}^{up}	Ramp up (discharging) regulation bid (MW)
Reg_r	Revenue from participating in frequency regulation
SOC_{dt}	State of charge of the battery
u_{dt}^{1}	Binary variable associated with discharging for the energy market
u_{dt}^{2}	Binary variable associated with charging for the energy market
z_{dt}^{1}	Binary variable associated with discharging for the regulation market
z_{dt}^{2}	Binary variable associated with charging for the regulation market

I. INTRODUCTION

Growing concerns about climate change over the last half a century have led to the development of greener technologies such as renewable energy and EV. lithium-ion batteries play

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an increasingly important role in both the expansion of EV use and the incorporation of renewable energy sources into the grid. lithium-ion batteries have allowed for the expansion of EV market because of their high energy density which makes them ideal for vehicles [1]. However, there are several concerns with lithium-ion batteries including their high cost and their environmental impact. Although the price of lithium-ion batteries has fallen significantly [2], it remains a hurdle for EV and the many other technologies that use lithium-ion batteries for their environmental concern. The scarcity of cobalt and other materials which are used in lithium-ion batteries is also a concern especially as our reliance on batteries for green technologies grows. One potential solution is to repurpose EV batteries for grid applications after they reach the end of EV life which is usually defined as 70-80% of their original capacity. Batteries provide a wide range of services to the grid including providing stability and reliability as penetration of renewable energy sources increases. lithium-ion batteries offer quick response making them ideal for frequency regulation. The best way to repurpose used EV batteries is to use it for grid applications since it can make high revenue in a short time.

Evaluations of the environmental benefits of using REVBs in grid applications do not follow a consistent method but do generally show a positive impact in cases where REVBs are used in place of a new BESS to reduce using more chemical materials, especially in combination with increased integration of renewable energy [3], [4]. Repurposing EV batteries avoids the manufacturing of a new battery and can replace polluting energy sources such as coal or fossil fuels for some applications which results in a reduction in greenhouse gas (GHG) emissions. However, reduction of GHG emissions is not the only environmental benefit, repurposing also extends the use of critical raw materials (cobalt) and resources with increasing demand such as lithium [3].

A variety of grid applications have been studied for REVBs considering their economic and technical viability. In 2003, Cready et al [5] provided an analysis of Nickel/Metal Hydride batteries performing services on the utility, commercial and residential scale. They found several grid applications to be profitable although with some uncertainty. Applications that involve a large battery or short battery lifespan proved the least profitable due to the high capital cost and short lifetime. Further research focuses mostly on lithium-ion batteries as they are generally favored in EV applications due to their high energy density. In 2011, Neubauer and Pesaran [6] found area regulation with REVBs to be profitable, while a few other services were likely to be profitable under some conditions. Several studies have found residential applications to be profitable under certain conditions and in some cases more technically feasible given that large scale applications will require a more complex control and management system and introduce additional safety concerns [7], [8].

Stacked services are a promising method of maximizing batteries use and profits. The economic benefit of performing stacked energy arbitrage and frequency regulation is explored in [9] and [10] but without considering battery lifetime. Although stacked services usually provide greater revenue, they often shorten the batteries life by increasing cycles. Frequency regulation has been shown to be highly profitable but also greatly increases the number of cycles performed. Increased cycling can be managed by setting a limit on the cycles performed per a given time period. Given the economic advantage of performing stacked services this paper will investigate REVBs performing frequency regulation and energy arbitrage at PJM market.

The lower capital cost is one of the primary advantages of using REVBs. However, market price of REVBs is challenging to estimate given the numerous methods of pricing that manufacturers may adopt and the constantly changing market for new EV batteries. Neubauer et al. [11] provides a broad analysis of the cost and technical considerations of repurposing. Considering the cost of a new battery, which they assume to be \$150 to \$250 /kWh, and various second life battery health factors, they estimate REVBs market prices to range from \$44 to \$180 /kWh for battery electric vehicles and plug-in hybrid electric vehicles. According to the BloombergNEF 2019 report, average EV battery prices had fallen to \$156 /kWh in 2019 and are predicted to reach below 100 \$/kWh by 2024 [2] making a range of \$45 to \$112/kWh more accurate for current market prices. However, the health factor calculation is dependent on the second life application and remaining life span, thus further investigation into the aging of REVBs may yield more accurate estimations of market price. Cole and Frazier [12] estimate the cost of 4-hr duration (battery can be fully discharged in 4 hours) Li-ion BESS to be between 325 and 375 \$/kWh in 2020. Estimations of REVBs cost must consider maintenance ,installation and degradation factors . This is elaborated on in Section III.

Several large scale REVBs projects have already been built demonstrating the technical feasibility of using REVBs for utility scale services. One such is a joint project by Bosch, BMW, and Vattenfall in Hamburg, Germany [13]. This BESS has an energy rating of 2.8 MWh and power rating of 2 MW and consists of 2600 repurposed BMW i3 batteries. The BESS has been providing interim storage for energy from a photovoltaic facility and for an EV fast-charging station. However, its size allows it to potentially participate in the regulation and energy markets. In this paper, we model our REVBs off this project, using information about BMW i3 batteries to estimate lifetime and cost.

The rest of the remaining paper is organized as followed. Section II introduces the mathematical model for optimal battery management. Section III includes a numerical simulation to provide a comparison between REVBs and new BESS. Section IV is the conclusion of this work.

II. MATHEMATICAL MODEL

The objective of this model is to manage REVBs with the goal of maximizing total revenue from the energy market and frequency regulation markets. This model can then be applied to both REVBs and new BESS. The model uses a time interval of one hour and therefore a time interval variable is omitted from the conversions between power and energy. The objective function and model are defined below.

$$max[Arb_r + Reg_r]$$

Energy arbitrage consists of buying and storing energy at low prices and selling at high prices. This allows battery owners to supply additional power in times of high demand thus reducing the strain on other energy sources. In addition power stored from energy arbitrage can also be used in frequency regulation market. The revenue generated from participating in energy arbitrage can be calculated as,

$$Arb_r = \sum_d \sum_t (A^b_{dt} + A^s_{dt}) lmp_{dt} \quad \forall d, \forall t \tag{1}$$

A^b_{dt} and A^s_{dt} are subject to the following constraints.

$$0 \leq A^s_{dt} \leq B^{PR} u^1_{dt} \qquad \forall d, \forall t \tag{2}$$

$$-B^{PR} u^2_{dt} \leq A^b_{dt} \leq 0 \qquad \forall d, \forall t \tag{3}$$

where u^1_{dt} and u^2_{dt} are binary variables that determine if the battery is discharging or charging for arbitrage. In this model, binary variables are used to make sure the battery is not charging and discharging at the same time or performing both services in the same hour. Equations (2) and (3) assure that the power bought and sold do not exceed the battery's power rating.

Frequency regulation is a service purchased from batteries owners by ISOs and RTOs. By charging or discharging power to and from the grid, batteries can balance the differences between power supply and demand, thus maintaining grid frequency and preventing large failures. The regulation market operates using a pay-for-performance mechanism which accounts for speed and accuracy more details about pay for performance payment can be found in [14]. BESS owners are paid based on the available charging or discharging power they bid ahead of time into the market. Then PJM sends a signal that determines how much of that bid they will need to actually supply. In the PJM market, there are two regulation signals: RegA which is primarily used for slower traditional regulation resources, and RegD which is primarily used for fast response resources such as batteries. The RegD signal ranges from -1 to 1 with negative values representing ramp down and positive values representing ramp up [14].

This paper uses the PJM Interconnection pricing method for frequency regulation. There are two parts to this method: capability clearing credit and performance clearing credit. The calculation also includes a performance score based on how well the signal is followed and a mileage ratio which represents the relative work of RegD resources compared to RegA [14]. The revenue generated from participating in frequency regulation can be calculated as,

$$Reg_r = \sum_d \sum_t (R^{MCCP}_{dt} + R^{MPCP}_{dt} M_{dt}) S_{dt} F_{bid,dt} \quad \forall d, \forall t \tag{4}$$

frequency regulating biding is subject to the following constraints.

$$F_{bid,dt} = F^{up}_{dt} - F^{down}_{dt} \qquad \forall d, \forall t \tag{5}$$

$$0 \leq F^{up}_{dt} \leq B^{PR} z^1_{dt} \qquad \forall d\ , \forall t \tag{6}$$

$$-B^{PR} z^2_{dt} \leq F^{down}_{dt} \leq 0 \qquad \forall d\ , \forall t \tag{7}$$

$$F^{up}_{A,dt} = D^{up}_{dt} F^{up}_{dt} / \lambda \qquad \forall d, \forall t \tag{8}$$

$$F^{down}_{A,dt} = -D^{down}_{dt} F^{down}_{dt} \lambda \qquad \forall d\ , \forall t \tag{9}$$

Equation (5) defines $F_{bid,dt}$ as a positive number representing the amount of power bid up (discharging) or down (charging). Equations (6) and (7) define the limits of regulation bidding based on the battery power rating and the binary variables z^1_{dt} and z^2_{dt} which determine if the battery is discharging or charging for regulation. These power limiting constraints, as well as (2) and (3) can be modified to limit the fraction of power which is dedicated to each service. Equations (8) and (9) define the actual power provided by the battery for regulation based on the RegD signal D_{dt} from PJM and the battery efficiency λ.

The model is also subject to the following constraints.

$$u^1_{dt} + u^2_{dt} + z^1_{dt} + z^2_{dt} \leq 1 \qquad \forall d, \forall t \tag{10}$$

$$D^{up}_{dt} \leq z^1_{dt} + u^1_{dt} + u^2_{dt} \leq 1 \qquad \forall d \forall t \tag{11}$$

$$-D^{down}_{dt} \leq z^2_{dt} + u^1_{dt} + u^2_{dt} \leq 1 \qquad \forall d, \forall t \tag{12}$$

$$SOC_{dt} = SOC_{d(t-1)} - (F^{up}_{A,dt} + F^{down}_{A,dt} + A^s_{dt}/\lambda + A^b_{dt}\lambda) \quad \forall d, \forall t \neq 1 \tag{13}$$

$$(1 - DoD) B^{ER} \leq SOC_{dt} \leq B^{ER} \quad \forall d\ \forall t \tag{14}$$

$$SOC_{dt} = (1 - 0.5 * DoD) B^{ER} \quad \forall d, \forall t = 1 \tag{15}$$

$$C = (DoD * B^{ER}) \sum_d \sum_t (F^{up}_{A,dt} - F^{down}_{A,dt} + (A^s_{dt}/\lambda) - (A^b_{dt}\lambda) \quad \forall d, \forall t \tag{16}$$

$$C \leq C_{max} \tag{17}$$

$$C_{DoD} = C_{100\%} / (DoD)^{kp} \tag{18}$$

Equation (10) ensures that the battery is only performing one service at a time. Equations (11) and (12) ensure that the regulation bidding is following the regulation signal while still allowing for energy arbitrage to happen instead of regulation when it is more profitable and power is available. Equations (13) and (14) define the state of charge SOC_{dt} of the battery and limit it using the battery energy rating B^{ER} and the maximum depth of discharge DoD. Equation (15) ensures that the battery will start every day with 50% of DoD. Given that our evaluation includes the capital cost of the REVBs, our model must account for the lifetime of the battery. This is done by counting cycles because cycling has a significant impact on lithium-ion battery degradation. In this model, a cycle is defined as the amount of energy discharged and then charged to reach the given DoD and return to a full SOC. Equation (16) defines the number of cycles performed by the battery by dividing the total energy charged and discharged during the simulation by the energy in one cycle at the given DoD. Frequency regulation often increases cycling which can result in very short battery lifetimes. Equation (17) sets a limit on the number of cycles that can be performed during the simulation.

III. SIMULATION

The goal of this simulation is to provide a profit comparison between REVBs and new BESS in performing stacked services including the capital cost. A comparison is also made between REVBs performing individual and stacked services. This optimization was run using mixed integer linear programming in GAMS software. In this work we are considering only DC power,thus the converter and other power electronics issues are ignored . The battery specifications, described in Table I, are based on the 2MW, 2.8 MWh project built by Bosch, BMW and Vattenfall using repurposed BMW i3 batteries [13]. The REVBs efficiency was taken from Heymans et al [7] to reflect the efficiency fade during EV life. The lifecycle is considered to be the number of cycles a battery can perform before reaching 80% of its starting capacity and for this simulation is estimated based on information about BMW i3 batteries in [13]. For a new battery, their estimation of 4600 cycles at 100% DoD was used. By extending their lifecycles curve to 64% of the original capacity, we were able to estimate the lifecycle of REVBs that ended its EV life at 80% of its original capacity. The REVBs lifecycle is estimated to be 3500 cycles at 100% DoD. We assume the battery should be operational for at least 10 years and limit the number of cycles per run accordingly.

Capital cost was estimated using grid scale lithium-ion battery price estimations from Cole and Frazier [12] and REVBs price estimations from Neubauer et al [11]. Cole and Frazier's estimate of $350/kWh for new BESS in 2020. For a new BESS, the total cost is estimated to be $480/kWh adding maintenance and installation costs, and the capital cost of a new battery for our simulation is $1,344,000. For the REVBs, an energy cost of $125 /kWh was estimated using the method in Neubauer et al [11]. Also, EV battery estimated by [2] to be $ 156/kWh in 2018 with a health factor of 0.8 . The total cost of re-purposing EV battery is estimated to be $310/kWh resulting in a capital cost of $868,000 including maintenance and installation which is higher then new BESS due to the fact that EV battery needs more technologies to make them grid scalable. The REVBs price estimate is likely high as most batteries will have a health factor lower than 0.8. A health factor of 0.8 was chosen to reflect a battery in very good health and provide an upper limit to price.

TABLE I
BATTERY SPECIFICATIONS

Energy Rating	2.8 MWh
Power Rating	2.0 MW
Cycle Life (new/repurposed)	4600/3500
Efficiency (new/repurposed)	0.95/0.8
Capital Cost (new/repurposed)	$1,344,000/$868,000

PJM historical data from 2019 was used which can be found on [15]. This data includes RMCCP, RMPCP, LMP, mileage ratio, performance score, and RegD signal. All data was converted to hourly data including RegD which was also separated into distinct up and down signals. The yearly estimate was multiplied by 10 years and then 10% sensitivity analysis was added to account for the decrease in energy prices as these markets becomes more competitive over the batteries lifetime.

First a sensitivity test was performed to determine the optimal depth of discharge. For these tests the batteries were assumed to have 80% efficiency and a lifecycle of 3500 at 100% DoD. Equation (18) describes the impact that DoD has on lifecycle. The value of kp varies for different types of batteries depending on how DoD impacts battery degradation. For lithium-ion batteries $kp = 1.1$ [16]. Equation (18) was used to calculate lifecycle for each DoD and set a new maximum cycles per day. The REVBs was evaluated performing both frequency regulation and energy arbitrage. The capital cost of the REVBs is assumed to be $868,000 including maintenance and instillation. Results from the sensitivity analysis can be found in Fig.1. and table II. Profits peak at 90% DoD so the following cases are conducted at 90% DoD.

TABLE II
DEPTH OF DISCHARGE ANALYSIS

DoD (%)	Yearly Revenue	Total Revenue	Net Profits
100	363711	3273403	2405403
90	365890	3293019	2425019
80	362625	3263629	2395629
70	361736	3255627	2387627
60	359215	3232939	2364939
50	356625	3209623	2341623
40	348520	3136678	2268678

The following simulation included four cases to demonstrate the benefit of stacked services and provide a comparison between new BESS and EV batteries. Case 1 shows an REVBs performing only energy arbitrage. Case 2 shows an REVBs performing only frequency regulation. Case 3 shows an REVBs performing stacked services. Case 4 shows a new BESS performing stacked services. Results from the simulation are presented in Table 3 and Fig.2.

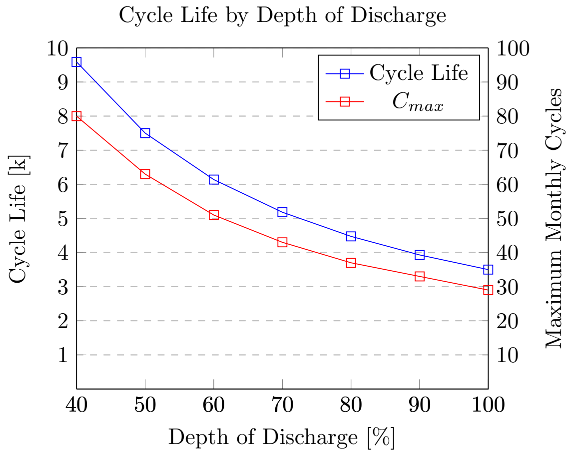

Fig. 1. Cycle life by depth of discharge

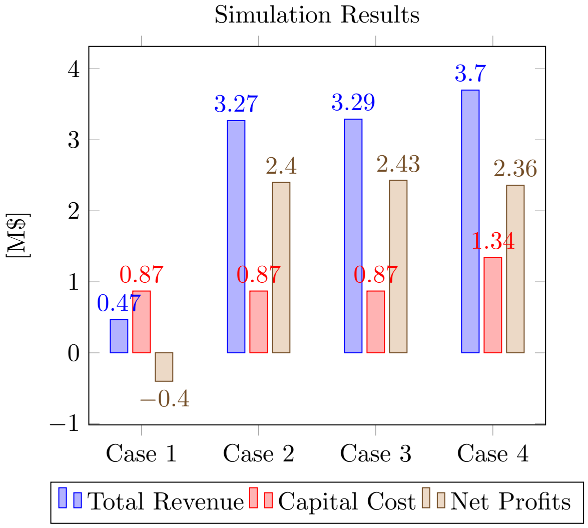

Fig. 2. Results of all cases

Case 1 shows that performing energy arbitrage alone is not profitable for this scenario given the high capital cost. Cases 2, 3, and 4 are all profitable with Case 3 coming out to the highest net profits. This supports the conclusion that REVBs can be equally if not more economically viable than new lithium-ion batteries in performing frequency regulation and energy arbitrage. The higher profits and lower initial investment make REVBs economically beneficial as well as being an environmentally beneficial alternative to new lithium-ion batteries.

TABLE III
RESULTS FROM CASES 1 TO 4

Case	Yearly Revenue	Total Revenue	Battery type	Net Profits
1	51862	466757	REVBs	-401243
2	3363522	3271703	REVBs	2403703
3	365890	3293019	REVBs	2425019
4	411489	3703403	new BESS	2359403

IV. CONCLUSION

In this paper a mathematical model to simulate REVBs performing energy arbitrage and frequency regulation is developed. The model is used to evaluate the economic viability of REVBs performing stacked services in the PJM market including the capital cost. The model is implemented in GAMS and solved using CEPLEX. It is shown that REVBS can provide higher profits than new BESS when capital cost, lifecycle, depth of discharge and health factors are considered. Given their additional environmental benefit, this supports further research and implementation of REVBs in place of new BESS for more grid applications like voltage support and black start. Further research should include more precise battery degradation models based on data from REVBs, and could explore stacking of other grid services. Government policies and subsidies with the goal of encouraging growth of sustainable energy solutions may also make REVBs use more economically advantageous. As we continue to move towards greener technologies in many fields, repurposing will remain an important option which should be considered.

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