Average Behavior of Battery-Electric Vehicles for Distributed Energy Studies

Francesco Marra, Chresten Træholt, Esben Larsen and Qiuwei Wu
Technical University of Denmark

Abstract – The increased focus on electric vehicles (EVs) as distributed energy resources calls for new concepts of aggregated models of batteries. Despite the developed battery models for EV applications, when looking at the scenarios of energy storage, both geographical-temporal aspects and EVs use conditions cannot be neglected for an estimation of the available fleet energy. In this paper we obtained an average behavior of battery-EVs, in relation to a number of variables such as current rates for charging and discharging, temperature, depth-of-discharge and number of cycles. An average approach was applied to calculate the influence of each variable on the battery energy and lifetime. The obtained results show that battery-EVs are non-linear time-variant systems which however can be modeled with good approximation if time, geographical location and battery use conditions are known.

Index Terms – Battery average behavior, distributed energy resources, grid energy storage, plug-in electric vehicles, electric vehicles

NOMENCLATURE
SOC State-of-charge: percentage of remaining battery capacity
DOD Depth-of-discharge: percentage of used battery capacity
SOH State-of-health: indicator of battery lifetime
HEV Hybrid electric vehicle are not pluggable into the electricity grid, not grid-interactive
PHEV Pug-in hybrid electric vehicle are pluggable into the electricity grid, grid-interactive
V2G Vehicle-to-grid operation: electric vehicles deliver power to the electricity grid

I. INTRODUCTION

The capability of battery-EVs to act as distributed energy storage in the grid is gaining increased attention. Research on smart-grids is addressing the possibility of using these vehicles for power balancing purposes in the power system by remote control of the charge/discharge process [1]. Key challenges for this role are the estimation of the available energy and lifetime of the batteries.

The main factors which characterize a battery-EV are depicted in Fig. 1. Whereas power, safety and cost are classic aspects of a vehicle, the energy and lifetime are more relevant in a distributed energy scenario and thus need to be assessed.

This paper proposes the concept of an average behavior of battery-EVs, in a real-life domain, where external parameters and several use conditions are taken into account. The final goal is the estimation of the available energy and lifetime of a battery-EV.

First, a number of battery models were analyzed to assess different battery performances with respect to different work conditions. The focus of the analysis was dedicated to lithium based batteries, due to their advantages compared with lead-acid and nickel based types, in terms of energy density, power density and lifetime. The analyzed models show the dependency of the battery performances on a number of variables and demonstrate their non-linear time-variant behavior.

As a second step, an assessment on battery-EVs use conditions was performed. The analyzed battery models were combined with probable cases of EVs utilization. Due to the fast charging capability of lithium batteries, the option of charging them at different current rates was considered. Current rates are addressed using the terminology “C rate”, where 1C indicates the nominal current of the battery in Ampere-hours. A trade-off on DOD values was defined in relation to the manufacturer constraints and battery life expectation. The variable of temperature was considered for both ageing assessment and for the evaluation of the available energy at low temperatures.

Finally, an average behavior of a battery-EV was derived using a mathematical average method. This approach wanted to mimics the behavior of EV fleets in localized areas, under a range of work conditions. The developed concept enables the estimation of available energy of an EV fleet, depending on a number of variables such as temperature, current rates, DOD and number of cycles.
II. BACKGROUND

From a fleet aggregator perspective, in a distributed energy scenario, plug-in EVs are considered an energy storage component by means of their battery pack [2]. The batteries are considered to be lithium technology based, since they represent the most promising option for EVs applications, in terms of volumetric and gravimetric energy density [3]. The battery of a generic EV is characterized by a time-variant non-linear behavior of energy and lifetime, which are dependent on a number of variables.

The theoretical energy of a generic battery-EV is described by the following formula:

\[ E_n = V_n \cdot C_n = V_n \cdot I_n \cdot h \ \ [KWh] \]  (1)

The battery pack energy \( E_n \) is expressed in KWh and is calculated by multiplying the nominal battery pack voltage \( V_n \) with the nominal battery capacity \( C_n \), expressed in Ampere-hours, \( I_n \cdot h \).

The battery lifetime is widely considered as the number of complete cycles that brings the battery capacity down to 80% of nominal capacity. The battery lifetime is therefore expressed in number of cycles.

Unfortunately, the real energy and lifetime of a battery are non-linear time-variant, which vary depending on climatic and use conditions. A number of lithium battery models were analyzed, looking at the development of some battery’s internal parameters [4]. These works asserted that:

- Low temperature strongly affects the charging/discharging capability and the available energy of a battery
- High temperature accelerates the energy fade and shorten the battery lifetime
- Full DOD accelerates the energy fade and shorten the battery lifetime
- High current rates, for both charging and discharging, accelerate the energy fade and shorten the battery lifetime

Energy fade and lifetime are assessed measuring the variation \( \frac{R}{R_{new}} \), where \( R \) is the actual internal resistance of the battery and \( R_{new} \) is the initial value of resistance. In [4] it was shown that the increase of the battery internal resistance, known also as ohmic resistance, lowers the battery discharge voltage, shorten the discharge time, increase the internal power losses and have a direct impact on the battery's power characteristics. As a consequence of the above effects, the rise of internal resistance indirectly affects the available energy and lifetime of a battery-EV. The three variables that mainly affect the battery internal resistance are the charge/dischARGE current rates, the DOD and the temperature. In [4] these variables were addressed to estimate the internal resistance rise over the number of cycles. The study justifies the use of the internal resistance as evaluation index of the battery state of health.

A. Charge/discharge current rates

The dependency of battery behavior on current rates was analyzed in [5]. In Fig. 2, the variation of internal resistance as a function of different current rates is depicted. Discharging an ideal battery, from fully charged state, with 2C rate would take 30 minutes, while discharging it at 5C rate would take 12 minutes. In [5] some tests were conducted with five different current rates and three different temperature values. It was observed that the battery may be fast charged at high current rates if a cooling system keeps the temperature under control. At a temperature of -20°C the 3C fast charging is not possible, while at 0°C the battery may be fast charged if a heating system is provided.

![Fig. 2 Internal resistance variation function of current rates](image)

These tests demonstrated that the temperature is an important variable when slow or fast-charging are employed.

B. Depth of discharge (DOD)

The DOD’s influence on the battery lifetime was investigated in [6]. The DOD is a fraction of the nominal capacity of the battery. Fig. 3 shows different trends of the internal resistance, function of three different DOD levels.

![Fig. 3 Internal resistance variation function of DOD](image)

In [6] it was demonstrated that the higher the DOD, the faster battery lifetime decreases.

C. Temperature

In [7] it was shown that a range of temperature conditions at the same current rate, 100% DOD, considerably influences the battery lifetime. In [4], it is possible to compare the internal resistance variation, between two values of temperature: 50°C and 20°C.
As depicted in Fig. 4, the study conducted under accelerated life tests, shows that the battery lifetime is about 3 times shorter if working at 50°C.

### III. BATTERY-EVS PRE-ASSUMPTIONS

The possible use conditions of battery-EVs have relevant implications on the battery behavior as described in the previous chapter. Different assumptions on plug-in vehicles utilization were done in order to assess the available energy and expected lifetime of the vehicles. At the scope, PHEVs, pure EVs and HEVs were compared for what concerns battery system design, DOD levels, current rates, temperature performances and number of cycles.

#### A. Battery system considerations

Since a few years ago, the majority of battery powered vehicles, both hybrid and plug-in were designed using nickel-metal-hydride (NiMH) batteries. The recent progress of lithium batteries has led to levels of energy density and power density which are more preferable than the other battery types. Much effort was dedicated to high power batteries for hybrid-electric vehicles (HEVs), since their main task is to assist the internal combustion engine (ICE), during high power demand operations.

We analyzed a number of sources [3]-[8] that show the different design concepts for battery systems in HEVs and plug-in EVs. As shown in Table 1, it is evident that the batteries for HEVs are quite different from those for EVs in terms of energy and power density. The energy density of EV batteries is significantly higher than that of HEV batteries. This is necessary because the EVs have to comply with the all-electric range, while the stored energy in the HEV units is not a critical requirement [3]. It is also clear from Table 1 that the power capability of the batteries designed for HEVs is much higher than those designed for EVs. This requirement follows directly from the lower weight of the HEV batteries and the need to transfer energy in and out of the HEV batteries at high efficiency. For the reasons mentioned above, lithium battery-EVs were assumed for the work.

#### B. DOD levels for Battery-EVs

We assumed from [3] that the DOD level for HEVs batteries is a very small percentage compared to their effective available energy, Fig. 5. Therefore the HEVs batteries can be used for many years before reaching the end of life condition.

On the other hand, the batteries for plug-in EVs require both high power capability and high energy density. In this case, since the battery is the main energy storage unit, the DOD level needs to be higher than the one of hybrid vehicles, 60 to 80%, in order to guarantee an acceptable vehicle range. Consequently the lifetime is in the range of 4-7 years, depending on the frequency of utilization.

In relation to the available data, the following pre-assumptions were made for the two types of plug-in vehicles, PHEVs and pure EVs:

- a PHEV has a battery energy of 10-12KWh
- a pure EV has a battery energy of 20-50KWh and nominal capacity in the range of 60-150Ah
- the generic battery-EV is equipped with a lithium-based battery, which is the most promising technology for electrical mobility at the moment
- PHEVs batteries are used up to 60% of DOD, while pure EVs are used up to 80% of DOD

#### C. Current rates for Battery-EVs

A number of charging options were defined in relation to the existing infrastructure and the available power connection points, single-phase or three-phase [9]. We have distinguished among three main use cases for battery-EVs, which are residential charging, public charging and public fast-charging.

---

**Table 1**

<table>
<thead>
<tr>
<th>Battery technology</th>
<th>Application type</th>
<th>Ah</th>
<th>Wh/kg at C/3</th>
<th>W/kg 95% eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid</td>
<td>HEV</td>
<td>25</td>
<td>26.3</td>
<td>77</td>
</tr>
<tr>
<td>Panasonic NiMH</td>
<td>EV</td>
<td>60</td>
<td>34.5</td>
<td>47</td>
</tr>
<tr>
<td>Panasonic NiMH</td>
<td>HEV</td>
<td>6.5</td>
<td>46</td>
<td>207</td>
</tr>
<tr>
<td>Panasonic NiMH</td>
<td>EV</td>
<td>85</td>
<td>68</td>
<td>48</td>
</tr>
<tr>
<td>Ovonic NiMH</td>
<td>HEV</td>
<td>12</td>
<td>45</td>
<td>195</td>
</tr>
<tr>
<td>Ovonic NiMH</td>
<td>EV</td>
<td>85</td>
<td>68</td>
<td>40</td>
</tr>
<tr>
<td>Li-ion</td>
<td>HEV</td>
<td>12</td>
<td>77</td>
<td>258</td>
</tr>
<tr>
<td>Salt</td>
<td>EV</td>
<td>41</td>
<td>140</td>
<td>90</td>
</tr>
<tr>
<td>Shim-Kobe NiMH</td>
<td>HEV</td>
<td>4</td>
<td>56</td>
<td>745</td>
</tr>
<tr>
<td>Shim-Kobe NiMH</td>
<td>EV</td>
<td>90</td>
<td>105</td>
<td>255</td>
</tr>
</tbody>
</table>

---

**Fig. 5** Lifetime characteristics for different DOD levels [3]
As shown in Table 2, for Use Case 1, a charger of 4KW is assumed; this is the largest charger that can be used for a standard outlet at residential homes without reinforcing the cabling [2]. The current rate resulting for Use Case 1 is derived by the power requirement, considering that the household demand is always a positive amount.

Use Case 2 entails the public charging, where single-phase or three-phase charging spots are available. In this case plug-in EVs can be charged with power and current rates in the range of 16A to 32A.

Use Case 3 entails the option of fast-charging of plug-in EVs. This option can be employed at a 3-phase charging spot only, due to the large amount of power needed. The fast charging case entails current rates of 5C or greater. If we consider that for PHEVs and pure EVs the battery capacity is generally in the range of 60Ah to 150Ah, it is straightforward to derive that the charging current of the fast charging case is always greater than 300A.

D. Temperature performances of Battery-EVs

We analyzed the characteristic curves delivered by some EV battery manufacturer in order to assess the temperature performances of the batteries.

The energy fade at different temperatures, as a function of the number of cycles, is depicted in the graph of Fig. 7 from [13]. It can be easily observed that using the battery at 23°C, with current rate of C/2, the measured lifetime corresponds to about 2600 cycles. While, using the battery at 45°C, with the same current rate, it leads to an overall lifetime of about 1500 cycles.

IV. AVERAGE BEHAVIOR OF BATTERY-EVS

In this paper, the average behavior of battery-EVs was analytically derived with mathematical average method. The average models were implemented to estimate the available energy and lifetime of the battery, using the analyzed battery models and the vehicle pre-assumptions performed in the previous chapter. The estimation of battery energy and lifetime was related to a number of variables which are temperature, DOD level, current rates and number of cycles. Therefore energy and lifetime can be described by the following functions:

\[ L = f(CN, T, DOD, CR) \]  
\[ E_A = f(CN, T, DOD, CR) \]

The lifetime \( L \) in (2) and the available energy \( E_A \) in (3) are both function of the following variables:

- Number of cycles, \( CN \). Energy and Lifetime are affected by the number of cycles. This variable counts the number of charge/discharge cycles of a battery-EV. If the vehicle is used in Vehicle-to-Grid mode, the number of cycles \( CN \) will increase accordingly.

- Temperature, \( T \). This variable strongly affects the battery-EV performances and lifetime. Low temperature conditions of e.g. -20°C, -10°C are very common at certain latitudes. The available energy is considerably reduced and at the same time the

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Charging options</th>
<th>Charging levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>USE CASE 1 Charging at home</td>
<td>1-phase or 3-phase</td>
<td>&lt;16A</td>
</tr>
<tr>
<td>USE CASE 2 Charging at Public charging spot</td>
<td>1-phase or 3-phase</td>
<td>16A - 32A</td>
</tr>
<tr>
<td>USE CASE 3 Charging at fast-charging public spot</td>
<td>3-phase</td>
<td>&gt;300A</td>
</tr>
</tbody>
</table>
charging process is not effective as for charging at ambient temperatures, e.g. 20-25°C. At higher temperature, e.g. at 45°C or above, it is demonstrated that the battery lifetime is negatively affected.

- **Depth-of-discharge, DOD.** The DOD level considerably affects the battery-EV lifetime and energy fade. It was analyzed that using the battery up to 100% DOD instead of 60% of DOD, can result in about 2000 cycles in difference, in terms of lifetime. Therefore battery-EV manufacturers limit the available DOD level, trying to find a good trade-off between vehicle range and battery lifetime.

- **Charge/discharge current rates, CR.** The current rates during charging/discharging strongly affects the lifetime and the energy fade of the battery. The design of a PHEV or EV is made considering an average current of around C/2 in a normal driving cycle and a peak current in the measure of C to 2C during high speed or accelerations [10]. If the use of the battery-EV is often characterized by high current rates during driving, the battery lifetime decreases. The same consideration is valid in V2G mode, when the battery-EV delivers energy back to the grid. On the other hand, if fast-charging instead of standard charging is applied, the battery lifetime decreases.

### A. Average available energy over DOD

The study on the average available energy over DOD was done considering both PHEVs and pure EVs, since these two types of vehicles can be grid interactive and can be employed as distributed energy resources. In this work, battery-EVs were assumed in discharge mode while driving or during V2G operation. The average available energy was obtained considering the vehicle pre-assumptions made in the previous chapter. The average method conducted to the result depicted in Fig. 8, where two different energy windows are represented for PHEVs and pure EVs respectively:

![Fig. 8 Available energy window for PHEVs and EVs](image)

From Fig. 8 it follows that for both vehicle types the available energy of the batteries never corresponds to the rated energy of the battery, as formulated in (1).

Lifetime considerations and an assessment on driving pattern performed in [10], leads to consider as available energy window for PHEVs, the 60% of the rated battery capacity. While for pure EVs it is common to use the 80% of DOD. The difference with the PHEVs energy window can be understood considering the different operation of pure EVs than PHEVs.

Considering the smaller range of PHEVs in pure electric mode, the frequency of deep discharge cycles would be higher than EVs. To guarantee an acceptable battery lifetime, battery manufacturers identified DOD levels of up to 60% for PHEVs. In pure EVs the battery is used and stressed for the entire driving cycle. For this reason battery manufacturers suggest DOD levels of up to 80%. This information can be managed at fleet operator level, in order to estimate the total available energy from EV fleets.

### B. Average available energy over temperature

In Chapter II, we have seen that the available energy of a battery-EV is strongly dependent on temperature conditions. It was shown how the high temperature negatively affects the lifetime of a battery. On the other hand, it was analyzed how the low temperature conditions influence the available energy and the charge/discharge performances of a battery.

In particular, the battery capability to release the stored energy or to accept the incoming power is much reduced at low temperature, even at low C rates. From a fleet operator point of view, when a large percentage of plug-in EVs are present, the location of such vehicles is important to estimate the available energy as a function of the temperature. An analysis was done using weather forecasts. The average method is valid in a relatively wide geographical area. The definition of a realistic geographical extension is made for two Scandinavian regions, since they are characterized by low average temperatures. Using the temperature forecasts at the time of the work [14], a spring day for Denmark and Norway, we calculated the average temperature, based on the minimum and maximum values.

![Fig. 9 Temperature values of Scandinavian areas](image)

As depicted in Fig. 9, different locations in Denmark have very similar temperature values. Therefore, an area similar to Denmark’s size, 43,000 Km$^2$, can be described with the same average temperature value. With the same procedure an assessment on the average temperature was made for Norway. The Norwegian case was particularly interesting in this context, since due to its length, an average value of the temperature could not represent the entire country. An average function was applied for the estimation of the temperature effects on the available energy of a battery-EV. A
number of battery manufacturer’s data were compared. The average behavior of a battery-EV over the temperature was calculated considering a temperature range between -20°C and 60°C.

The results depicted in Fig. 10 show that it is reasonable to model the effect of low temperature, at -20 °C, with a reduced capacity of up to 60% of the rated one. This information can be used to estimate the available energy resulting from battery-EVs fleets all around the country. The average method doesn’t consider the option of vehicle connection in garages, but it focuses on external location of battery-EVs.

The same assessment was made for high temperature conditions. The same data from the different battery manufacturers were considered. The analysis led to the result that temperatures of 40-45°C are a good working region for the total release of the stored energy, but at the same time the use of batteries at these temperature levels reduces the lifetime.

At the higher temperature of about 60°C, the available energy is still very high, 10% less of the nominal one, but the battery lifetime is drastically reduced. Ambient temperatures of 20-25°C are indicated by battery manufacturers as optimal working region for battery lifetime. This average method depicts the behavior of a fully charged battery-EV, considering a 100% SOH. The average was calculated considering a number of battery datasheets. As a result, it was possible to model the available energy with a linear trend within the temperature range of -20°C to 60°C. In a scenario of distributed energy resources, under low temperature conditions of e.g. -20°C to -10°C, the energy amount resulting from a fleet of vehicles doesn’t correspond to the stored energy in the batteries. Also, this amount of energy cannot be derived anymore by the SOC indicator, since the temperature introduces non-linearity in the system.

C. Average lifetime

We have seen that the lifetime is not a key issue if we look at a daily or weekly time interval. Anyway, when looking at a long-term scale, the lifetime is a key factor for a realistic and correct operation of EV fleets. We have analyzed lifetime characteristics for EV applications from a number of battery manufacturers. For the average lifetime calculation we considered the lifetime curves obtained at discharge conditions of 1C rate and ambient temperature of 20-25°C. This choice comes from two considerations made on EVs driving pattern studies [10]:

- the average current during a driving cycle is considered around 1C, this value takes in account some accelerations that may use 2C rates for about 30 seconds in highway regimes
- the battery pack is supposed to work at the average temperature of 20-25°C, since a cooling system is always provided with the battery system

Based on these considerations, the average method was applied to the battery data reported in Table 5. All data were supplied from different battery manufacturers.

Table 5

<table>
<thead>
<tr>
<th>Battery manufacturers</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery type</td>
<td>LFP</td>
<td>LFP</td>
<td>LFP</td>
<td>LiPO</td>
</tr>
<tr>
<td>Current rate</td>
<td>1C</td>
<td>1C</td>
<td>1C</td>
<td>1C</td>
</tr>
<tr>
<td>DOD</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Lifetime</td>
<td>1750</td>
<td>1600</td>
<td>1700</td>
<td>1450</td>
</tr>
</tbody>
</table>

In relation to Table 5, the average behavior of battery-EVs is obtained applying the mathematical average. The resulting average lifetime is depicted in Fig. 10. The vertical line represents the median and it intersects the 80% of retained energy, on the y-axis, after 1631 cycles. The retained energy is assumed 100% at initial conditions.

V. CONCLUSIONS

In this paper the average behavior of battery-EVs for distributed energy studies was modeled.

Two battery factors were addressed as key parameters for active grid integration of electric vehicles: the energy and the lifetime. An analysis on battery models, described in other publications was conducted as basis for the work. The available energy and the lifetime were modeled considering...
their non-linear and time-variant behavior with respect to a number of variables such as temperature, depth-of-discharge, current rates and number of cycles, using mathematical average method. A definition of EV use cases was given and the possible battery working regions were identified. An average behavior was finally derived using the concept of equations (2) and (3), and calculating the average based on the available data.

The obtained results have shown that the energy and the lifetime of EV batteries vary depending on different work and ambient conditions. To preserve the battery lifetime, the DOD level should not exceed the 80% for pure EVs and 60% for PHEVs. Discharging a battery up to 100% instead of 80% of DOD could result in about 1000 cycles of difference in lifetime. Using the battery at 45-50°C can halve the lifetime. At low temperature, -20°C, the available energy is about 40% less than the rated energy. Charging or discharging the battery at 2C rate instead of 1C or C/2 can halve the lifetime.

A conclusion could be derived saying that a certain percentage of battery-EVs in the grid, in a relatively wide geographical area, can be modeled with good approximation if time, geographical location and battery use conditions are known. When modeling fleets of battery-EVs, neglecting variables such as temperature, DOD, current rates and number of cycles, may result in remarkable errors of available energy.

VI. REFERENCES

[13] Valence Technology, “Lithium Iron Magnesium Phosphate (LiFeMgPO4) Battery Modules”, online datasheet