

Considerations in Estimating Battery Energy for Hybrid and Electric Vehicles

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ABSTRACT

As batteries become a major component of numerous advanced vehicles, significant efforts have been allocated towards characterizing and estimating battery energy capability over the lifetime of a vehicle. Currently, battery State of Charge (SOC) is one of the primary values used for this characterization; however SOC usage has several issues when implemented in Electric Vehicle (EV), Hybrid Electric Vehicle (HEV), and Plug-In Hybrid Electric Vehicle (PHEV) systems. One of the main issues with reporting battery SOC as a characterization of battery energy capability is that it only gives a percentage of the energy available to the operator. SOC does not accurately represent the true capability or capacity of the battery, and thus fails to account for the impact to capability with respect to battery size, age, and recent operational history. These inaccuracies of SOC characterization are magnified as it is incorporated into the control systems of EVs, HEVs, and PHEVs, which are typically configured to process only characterizations of the “rechargeable” Energy Storage System (ESS) in units of energy. As such, significant attention has been given of late to calculations and algorithms related to the assessment of the energy remaining in an ESS [1]. In this document, these techniques are referred to as State of Energy (SOE) estimation. This is because this term is directly tied to energy efficiency. This paper seeks to identify issues and opportunities in the estimation of battery energy for EVs, HEVs, and PHEVs.

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INTRODUCTION

Recent developments in vehicle technologies have led to new automotive architectures that can be used as alternatives to conventional internal combustion engine (ICEs) based vehicles. Two of these architectures of particular interest are Electric Vehicles (EVs) and Hybrid-Electric Vehicles (HEVs). An EV uses a battery-driven electric traction motor to provide propulsion to the wheels, while, an HEV employs a combination of ICE, fuel cell or related source, as well as electric power. A Plug-In Electric Vehicle (PHEV) is simply an HEV capable of plug-in charging. Both HEV and PHEV architectures are capable of demonstrating improved fuel economy and reduced emissions compared to their ICE counterparts.

In EV, HEV, or PHEV variants, it is typically the presence of a rechargeable Energy Storage System (ESS) containing a battery that provides the electrical energy necessary for primary motive force, energy buffering, and regenerative energy capture. Such batteries exist in numerous

forms, including lead-acid, nickel-cadmium, nickel-metal hydride (NiMH) and lithium-ion (Li-Ion) electrochemical cell configurations. An electrochemical cell can be described as a device that converts chemical energy into electrical energy or vice versa when a chemical reaction is occurring in the cell. Typically, an electrochemical cell will consist of two electrodes - one negative and one positive (referred to as the anode and cathode respectively) within a medium (known as an electrolyte) with electrode reactions occurring at the electrode-solution surfaces. The electrolyte provides the essential ionic conductivity between the anode and cathode. An ion-permeable, electronically non-conductive material or spacer is typically placed between the anode and cathode in order to prevent short-circuits between the two electrodes. In simple terms, a battery can be described as a device that stores electrical energy using electrochemical cells.

A battery based Energy Storage System (ESS) can be described as one or more batteries that are thermally managed, structurally designed, electrically protected, and

electronically controlled. Other ESS configurations are possible with possibilities ranging from capacitors to pneumatic energy storage systems; however the focus of this work is on the more prevalent battery based ESS. The basic design requirement considerations for an ESS within an EV, HEV or PHEV are as follows:

- Thermal Management

- Life, performance and safety of an electrochemical cell are closely related to its temperature. Passive and active systems (such as liquid cooling) may be used.

- Charging Control and Cell Equalization

- Certain chemistries are sensitive to overcharging and over discharging and require controls to prevent this from occurring.
- Electrochemical cells within a pack typically vary in capacity, internal resistance, and self discharge. When these cells are connected in series manner and operated together, the cell to cell variation (particularly in large series strings) will result in the individual cell voltage to diverge with time. If this divergence is not managed through mechanisms like “cell balancing” or “power management” or state of the art cell manufacturing and pack construction techniques, pack life and performance may be reduced.
- Most ESSs in EV as well as strong HEV and PHEV architectures contain batteries that are constructed with a large number of cells in series. Thus, ESS performance is limited by the weakest cell element in the series chain.

- State of Charge (SOC) and/or State of Energy (SOE) and/or State of Function (SOF) Computation

- Current, temperature, and voltage must be monitored to accurately compute the amount of charge/energy remaining in each cell/module/pack as well as other parameters critical to vehicle operation available within the ESS for use by the EV, HEV or PHEV.

All this information needs to be communicated to various other vehicle controllers. For example, this information allows, an EV, HEV or PHEV operating system to determine the amount of allowable regenerative energy to capture, when the ESS is full or empty (i.e. with respect to plug-in charge), if a particular maneuver is feasible under the current prevailing conditions, and in the case of an HEV or PHEV, how and when to use the internal combustion engine (ICE). What is clear is that many devices within an EV, HEV or PHEV require an accurate reporting of the useful energy related characteristics of an ESS in order to recognize when additional charging is required or when discharging is appropriate. One technique of reporting these characteristics for an ESS is through the calculation and reporting of SOC.

Given the current regulatory, vehicle development, and test procedure implications of identifying ESS available

energy, and to better discuss the challenges of and alternatives to SOC utilization, a collaborative study was undertaken by Navistar and Argonne National Laboratory (ANL) to review techniques used to estimate energy in an ESS. Given the range of estimation techniques, this study also aimed to provide a few examples of how the different estimation techniques can result in different energy estimates and thus influence vehicle behavior in varying ways.

STATE OF CHARGE

State of Charge (SOC) can be described as the present coulomb delivery capability of an electrochemical cell expressed as a percentage of total coulomb delivery capability when charged to the utmost of its capacity. Energy, from an electrochemical perspective, may be expressed in Ampere-Hours, or Ah by calculating integration of current with respect to time, starting from some known initial condition of the electrochemical cell (defined as either empty or full). Thus, SOC may be defined as a function of the Ampere-hour capability and capacity of an electrochemical cell:

$$SOC = \frac{Ah_{CAPABILITY}}{Ah_{CAPACITY}} * 100\% \quad (1)$$

This definition does not directly account for prevailing conditions. SOC as defined is a dimensionless quantity and does not directly measure energy. However, both $Ah_{CAPABILITY}$ and $Ah_{CAPACITY}$ are defined with respect to the rate and magnitude of charge and/or discharge, age, temperature, the definition of “empty” as well as the definition of “full” charge for an electrochemical cell. In order to understand the impact of this relationship, it is important to further define capacity and capability.

Capacity may be defined as the present coulomb delivery capability of an electrochemical cell which has been charged to the utmost of its potential to accept energy under the prevailing conditions of operation. The actual capacity of the cell may vary substantially from the rated capacity determined by the cell manufacturer. In addition, the actual capacity may be affected by the operational history (i.e. charge and discharge frequency and magnitude), age and prevailing conditions of the cell.

Capability may be defined as the present energy content of the electrochemical cell that can be removed to perform practical work under the prevailing conditions. For example, a point where the load and cutoff voltage can be defined as “empty” (i.e. point where there is no more “useable” energy left). Capability in units of energy is the present coulomb delivery capability of an electrochemical cell at any point during the cell's operation.

In order to know the SOC of an electrochemical cell with any certainty, the two quantities in [Equation 1](#) must be measured carefully. First, the electrochemical cell must be discharged until “empty” under a set of well-defined conditions in order to establish the quantity of remaining

energy. Second, the electrochemical cell must be recharged until “full” and completely discharged again under the same conditions so that the total usable energy capability may be known. This is the primary laboratory approach to determining SOC [2], and it is the standard against all other methods of SOC estimation are judged. This method is often referred to as the “direct measurement” method and it is highly dependent on the criteria for “full” versus “empty” used. There are three main issues with this method. The first is that the test itself cycles the cell, and may have an aging effect. The second is that it is clearly not a practical method for measuring electrochemical cell performance in real-time for use within a vehicle environment. The third is that EVs, HEVs and PHEVs have ESSs with large numbers of electrochemical cells. Each cell in reality will have a slightly different “empty” and “full” point. This is compounded by how one chooses to determine which SOC to report at module or pack level - the minimum, the average, the mean, the maximum or some other representative SOC.

As a result, numerous methods have been investigated in order to calculate SOC. A list of the more common methods can be found in Table 1 in the Appendix. Each methodology has its own merits, depending on the electrochemistry, pack configuration and the degree of characterization required. Perhaps the most common in-vehicle ESS SOC estimation method is the use of “Coulomb Counting”. This algorithm works by establishing in advance the total usable energy storage capability of an electrochemical cell under a wide variety of conditions and storing this information within a look-up table (usually respective of module or pack level) in a vehicle controller. The SOC may then be calculated by current integration, with the appropriate value from the look-up table being substituted as the variable $Ah_{capacity}$. This estimate can be very accurate over short periods of usage, but this is entirely dependent upon the accuracy of the starting value of SOC from which the calculation propagates over time. If the cell/module/pack has not recently been fully charged or fully discharged, the initial SOC cannot be known with any certainty. This will corrupt the accuracy of any subsequently calculated SOC. Even if the initial value is known exactly, measurement error in the current sensing device will accumulate over time and the accuracy of calculated SOC will eventually be compromised.

The bulk of the remaining approaches, which may be used alone or in concert to exert a correcting influence on the current integration method, utilize the inference of SOC from an estimate of the battery open circuit voltage, V_{OC} . The “ideal” dependence of V_{OC} on SOC is shown in Figure 1 for a few chemistries. Note that the nature of the relationship can vary significantly with chemistry. For some electrochemical cells, the relationship is weak and complicated by the presence of hysteresis, as is the case for Li-ion with an iron phosphate cathode (LiFePO₄), or NiMH. This makes it

difficult to correlate a given value of V_{OC} with a unique SOC value. Assuming, however, that a discernable, monotonic dependence of V_{OC} on SOC exists, and that the effects of hysteresis can be taken into account, V_{OC} can be a valuable indicator of SOC.

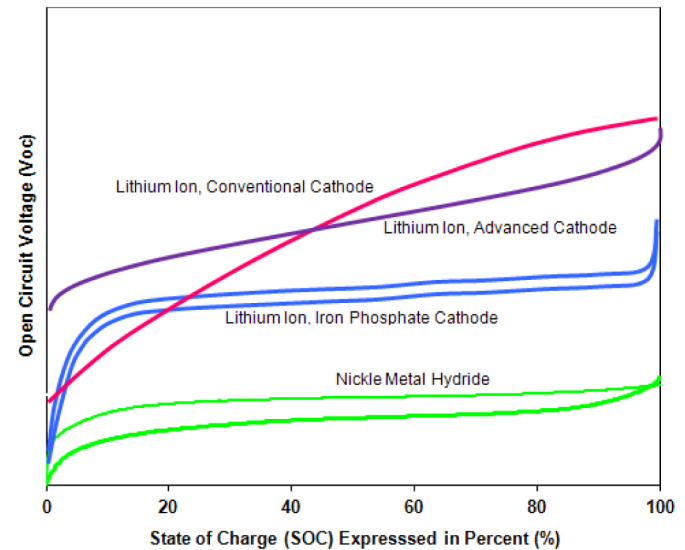


Figure 1. V_{oc} Dependence on SOC Examples¹

Much like estimating SOC from V_{OC} , calculating V_{OC} itself may also prove to be quite difficult and subject to uncertainty. V_{OC} may be measured when the electrochemical cell is at rest and has equilibrated, but these conditions are seldom met in an EV, HEV or PHEV application. V_{OC} may also be estimated when the electrochemical cell battery is under load through the use of a model (i.e. equations, circuits, etc.) of the electrochemical cell. Typically, an algorithm is devised whereby measured current and voltage are supplied as inputs, and the values of the various parameters (including V_{OC}) are determined. The model is not a perfect representation of the electrochemical cell under all operating conditions - particularly when extrapolated to module and pack level where elements such as position, cell balance and physical pack construction may play a role. Another reason is that a certain level of excitation is required in order for the algorithm to converge on a solution for the model parameters. For these reasons, the reported V_{OC} (and corresponding SOC) may suffer periods of instability. Despite these issues, in the long-term, the SOC determined by this method has been found to trend toward a value that is generally in agreement with that found by the laboratory test method and is far superior to that of an ampere-only “Coulomb Counting” based SOC calculation. Increasingly accurate current sensing has the ability to make the ampere counting approach more robust and accurate, but it does not replace the need for other V_{OC} based approaches. Often, in an EV, HEV or PHEV

¹Navistar internal cell chemistry survey testing 2010-2011

application, both Coulomb counting and V_{OC} based approaches are used to ensure SOC accuracy at all times (i.e. particularly when an EV, HEV or PHEV has been sitting for a long period of time unused or if the ESS has undergone a large temperature differential while unused. Unfortunately, problems still may occur with some cell chemistries such as with a LiFePO_4 cathode which exhibits only a very small change in voltage over most of the charge/discharge cycle. While this characteristic is beneficial in a vehicle application since cell nominal voltage does not change appreciably as the cell is discharged, thus ensuring an excellent “percent SOC per XX kilowatt hours”, the actual cell voltage is not a good measure of the SOC of the cell. Additionally, any inaccuracies of the SOC parameter are magnified as SOC is incorporated into the control systems of EVs, HEVs and PHEVs, as these vehicles are typically configured to process only characterizations of the ESS in units of energy.

While, SOC continues to be the most common approach, State of Energy (SOE) approaches are becoming more desirable because they allow for better range and ESS energy availability determination. SOE reports the state of the ESS as a representation of energy with respect to time (i.e. a true fuel gauge).

FUEL GAUGING

ESS energy assessment using SOC at the electrochemical cell level is not unlike the fuel gauge in a gasoline or diesel tank. While this comparison may work in many instances, this analogy does not completely hold true, especially as an ESS gets larger and the number of cells/modules/packs increases. [Figure 2](#) shows the fuel tank levels in a conventional gasoline or diesel vehicle, which can be used as the basis for a battery based analogy relating to a battery “fuel” gauge.

A basic fuel gauging system in a gasoline or diesel vehicle relies on a sensing unit connected to a potentiometer. As the fuel is used and the tank empties, the float drops and slides a moving contact along the resistor, increasing its resistance. The sensing unit monitors current as the resistance changes and the level in the tank is determined. Within standard operating conditions and under consistent operation, each gram of fuel that is consumed equates to the same amount of kilowatts of energy produced, whether the gram of fuel was burned when the fuel tank was full or when it was empty. Furthermore, it is not uncommon to find ICE operating algorithms which rely on the conversion of grams of fuel to torque produced.

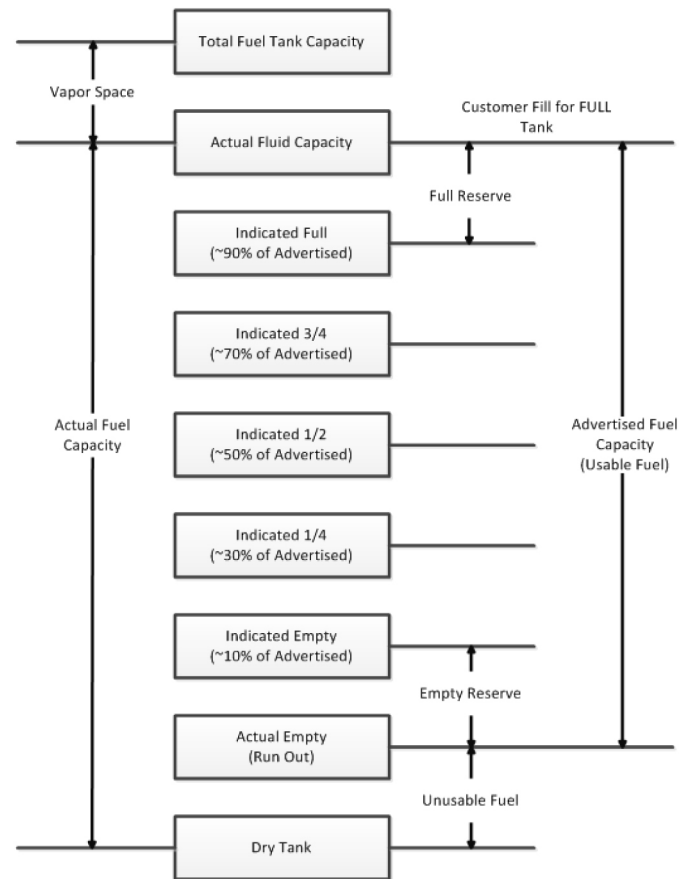


Figure 2. Fuel Tank Analogy

SOC ESTIMATION AND THE FUEL TANK ANALOGY

The fuel tank analogy of [Figure 2](#) with respect to an electrochemical cell may be proposed as:

- Capacity = the volume of the fuel tank.
- SOC = the volume of the fuel / the usable volume of the tank.
- Open Circuit Voltage (V_{OC}) = the height of the fuel level.

Voltage is defined as the electric potential energy per unit charge and is measured in joules per coulomb (or volts). Voltage is often referred to as “electric potential”, which then must be distinguished from electric potential energy by noting that the “potential” is a “per-unit-charge” quantity. In [Figure 1](#), it is clear to see that the electric potential is changing as the electrochemical cell moves from full to empty, and that this change is not linear as one might expect from the discharge of gasoline or diesel fuel in a tank, hence issues relating to SOC as an appropriate fuel gauge. In addition, in chemistries which exhibit hysteresis, the voltage is dependent on whether the cell is charging or discharging or at equilibrium. This is complicated by the fact that within a typical battery-based RESS, no cell is truly identical to

another. It is not uncommon to see cells that are adjacent to each other with different reported SOC values, self-discharge rate, cell impedance, capacity, and aging. These differences may be a result of cell manufacturing variability, temperature differentials, or pack construction. After several charge and discharge cycles, this may result in increased voltage differences between the individual cells. This effect will impact pack operation as several cells may no longer be able to be properly charged, with the possibility of some cells being over or undercharged. This will decrease the overall lifetime of the battery.

In order to make this analogy and use SOC as a robust “fuel” gauge, one must assume two “truths”, which are generally not true for most in-vehicle ESS uses. First, that the height of the fuel tank remains unchanged with aging. Second, the shape of the fuel tank or rather the allocation of reserve, usable and unusable fuel levels remains unchanged with aging. Unfortunately, when considering an electrochemical cell, the width of the tank will change and as a result, the volumes within the tank will change. This point emphasizes the need for a good understanding of current cell capacity and V_{OC} (the voltage of the cell under no load) as this knowledge is required in order to balance cells successfully and predict SOC. Since it is very difficult to measure actual SOC at a capacity versus capability level in real-time, the calculated deviation from the actual SOC must be clearly understood. While predicting SOC has improved significantly over the past few years due to advances in micro processing capabilities and chemical characterization; significant gaps still remain. One SOC calculation method is not easily ported to another chemistry, and this is a problem in vehicles such as medium and heavy duty vehicles where the pack may be replaced several times in one vehicle application over the lifetime of the vehicle.

ESS ENERGY ASSESSMENT STABILITY

Stability may be quantified as the ability to track a standard (agreed upon) reference signal. Commonly, the definition of this standard reference signal for SOC is a current integrated SOC based on a trusted source of current source (cyclor current sensor, shunt, etc.). Stability is preferred as it makes it easier to “predict” EV, HEV or PHEV performance; however accuracy is required for safety [3, 4]. This is why a consistent and measurable fuel gauge is more than a fringe benefit.

For example, V_{OC} lookup type SOC estimation technique may result in large jumps of SOC when the algorithm corrects itself due to a resting battery or a new V_{OC} reading. A practical example of this this scenario would be a resulting jump in SOC is due to the V_{OC} based estimate being reset at vehicle key-on, following the battery resting during the pause between the first and second UDDS cycles.

An additional example of SOC adjustment, which has been derived from vehicle testing done at Argonne National

Laboratory, can be seen in Figure 3. This data was recorded during back-to-back accelerations and the SOC as reported from the vehicle CAN bus can clearly be seen to change around 440 seconds. Interestingly, the net accumulated energy measured directly from instrumentation of the battery current and voltage does not change during this time period, which suggests the SOC update was due to factors other than battery net energy change. As with the previous hypothetical example, this shows how SOC may need to be updated due to battery usage that is not necessarily related to energy flow alone.

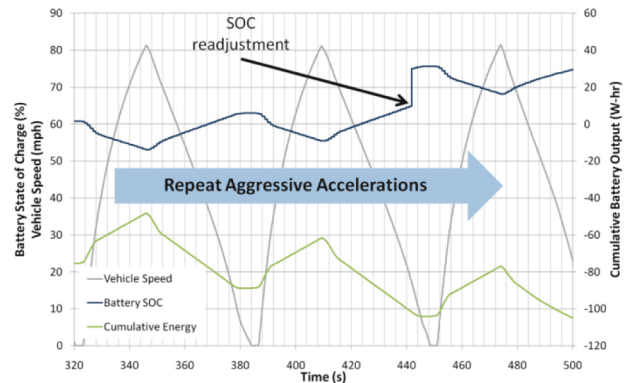


Figure 3. SOC Adjustment during Repeat Accelerations

Moreover, SOC may not always be the optimal available energy signal to use for vehicle control and operation due to its inherent variability and difficulty to estimate. The reporting of SOC alone gives an incomplete description of the state of the RESS, since the simple percentage says nothing about the relative size of the ESS. By determining the energy capability and energy capacity in quantities of energy (kWh, kJ, or the like) by accounting for the voltage at which the ESS operates, one can determine the amount of energy actually available to do meaningful work, and the amount of energy that is lost as heat. This energy capability is often referred to as SOE.

ESS ENERGY AVAILABILITY AND VARIABILITY TESTING

In order to better understand energy availability versus variability, the following Charge Depletion (CD) test procedure was developed.

- Charge the pack/module/cell at C/1 rate until the maximum cell voltage is reached (referred to as V_{MAX}). This voltage represents the 100% SOC/SOE point. The charge should be conducted using a constant voltage methodology (i.e. hold voltage until current is equal to approximately 1A).
- Rest the pack/cell for 30 minutes (or longer if polarization or related effects are a concern with that particular chemistry).
- Discharge the pack/module/cell to the proposed usable CD upper limit value (i.e. the effective open circuit $V_{CD upper}$).