Lithium battery: diagnostics and lifespan.
Application to the range estimation of an electric vehicle

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Abstract: Electric vehicles have a relatively long charging time and a relatively short range. Estimating a vehicle's consumption and range is therefore crucial. Range will depend on the average speed, top speeds, ascent and descent, battery temperature and battery condition. Judging the range of a vehicle is thus not a directly linear function of the distance to cover. This nonlinearity leads to mistrust, where a user cannot have total confidence in electric vehicles (bicycle, scooter, car ...). Moreover, the fail of only one cell of the battery can reduce drastically the range or even lead the vehicle to stop. The user must be able to diagnose the battery and its state of health to see if the proposed trip is feasible. This article presents a simple strategy to monitor the behavior of the battery during charge and discharge and provides a quick diagnosis of each element and also of the whole battery. Then, it's possible to determine the range remaining in a vehicle's battery based on all the above parameters. To find out if a vehicle can make a given journey without recharging, a web application for estimating the vehicle's consumption was completed and successfully tested.

Keywords: lithium battery, diagnostics, calculating range, balancing, eco marathon, velomobile, ebike.

1 Introduction

While electric vehicles have an increasing importance in the field of transport, the "range remaining" gauge can cause problems on irregular long journeys where energy consumption may reach up to 80% of the battery's capacity. The user does not know if there will be enough energy left or if a stop for recharging is needed. This anxiety can be moderated by a significant charging infrastructure [1]. However, the presence of these recharging points does not minimize the potentially annoying time taken to recharge. There have been numerous publications offering more or less sophisticated methods of establishing the battery's state of health (SOH) and state of charge (SOC) based on its technology [2], [3]. However, the resulting data cannot be used by a non-expert who simply wants to know how far the vehicle can still travel without a problem. The range will depend on the use, in other words on the route: how many accelerations, the top speed, the sum of positive and negative altitude changes, the kind of road (grainy or smooth), traffic conditions… In addition, the way the accessories are used is also very important, such as heating, air conditioning, lighting, car audio...

Consequently, in this article, we will answer the following questions:

- How the battery condition can be established?
- How a diagnostic can be run on the battery without special equipment?
- How can be estimate the lifespan and reliability of a battery?
- What management strategy can be adopted to extend the battery life?
- What strategies are can be used to estimate the remaining range and not cause anxiety of the end-user?

1.1 General context

Obviously, it is possible to increase the energy capacity of the battery leading to an increase of the vehicle's cost (0.5 €/Wh price of market in 2016 for lithium battery). Knowing that a battery's capacity decreases over time even if it is not in use (calendar ageing), such an increase in capacity may not pay for itself within the useful life. Therefore, having a battery with a high energy capacity is not at first sight ideal. The solution of exchanging an empty battery for a full one requires considerable infrastructure and investment. Moreover, such a solution is not viable for a large country with low population density. Furthermore, the outcome is a system of battery rental, a business strategy not suitable for many consumers, especially where a vehicle is little used while rental expense remains the same.

Given the current transitional nature of the energy field and the demand for minimization of energy consumption, individual and ultra light vehicles are coming on to the market. These vehicles have emerged in challenges such as the Shell Eco-marathon.

1.2 French situation

The average French commuter covers 26 km in 54 minutes. 50% of these trips are made by an unaccompanied driver [5]. 31 million French drivers drive 11,000 km per year on average.

Between 1994 and today, these numbers have changed only slightly, whether in rural or urban areas. Other societal studies show that, on average, Europeans drive more than 200 km on a return journey 8 times a year.

Since 2010, e-bikes (electric bike) have been used and tested in the Aisne IUT. With a range of 200 km at average speeds of 45 km/h, these velomobile have covered 20,000 km since 2013 [7], [8]. These prototypes are equipped with different battery technologies Lithium NMC, Lithium NCA, LiFePo4 from various manufacturers. In contrast, the sizing and energy management strategies are identical.

2 Electric cycles (velomobile)

Since 2010, ultra-light bicycles have been used every day on the road to test their reliability and their range. The lighter a vehicle, the less energy it consumes [7], [8], [9]. With electrification, fully faired tricycles can achieve top speeds of 80 km/h on the flat.

Fig. 1: Various prototypes of motorized electric cycles fully faired (50 kg to 85 kg)

The battery supplies a voltage of 72 V with an energy capacity of 20 Ah and a limitation on the battery current of 40 A or 2C (2 times the energy capacity). The power of the engine is 2880 W. Conventional electric bikes (e-bikes) have also been produced with the same performance.

In recent years, the LiFePo4 elements have become dominant because they offer a good compromise between price, energy capacity mass and volume and safety in use.

The batteries and chargers of these prototypes have been made in the laboratories. The chargers have integrated balancer feature and a charging current programmable from 1C to 0.1C. All the voltage curves of each element are viewable and recordable during charge and discharge. During charging, the internal resistance of each element is measured every minute. Discharge benches were also made in order to test the accumulators (in thermal chambers: ou est la temperature ???), as shown in the figure 2.

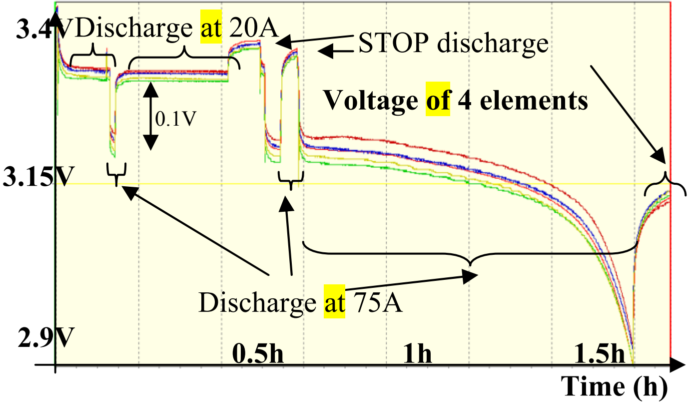


Fig. 2: Voltage versus time during the discharge of 4 elements LiFePo4 90 Ah.

However, the vehicle itself is a full-blown test bench with onboard instrumentation.

The fail of only one cell of the accumulator (self-discharge resistance, low internal resistance or energy content relative to other elements, heating of the component) detected by the electronic battery monitoring module ("Battery Management System" or BMS) will cause the discharge to stop and the engine of the vehicle at the same time! Indeed, an increase in the internal resistance of an element will cause a voltage drop below the critical threshold (cut-off voltage) and the BMS will stop the discharge well before all the other elements are completely out of charge. To avoid this situation, it is important to diagnose the health of each battery cell in real time. The reliability rate will, what is more, depend on the number of elements used in the accumulator, as will be demonstrated in the following section.

3 Reliability rate of an accumulator

Wiring the cells in series provides more onboard power by adding the cell voltages and provides the desired voltage level at the controller. However, having battery cells in parallel allows a greater current intensity to be available, with an acceptable discharge current per element. The assembly in parallel allows the reduction of the equivalent impedance by taking into account the number of branches in parallel, compared to the accumulated resistive effects in the serial assembly.

Given the slight differences in the internal resistance of the battery cells, imbalances of charge and discharge may occur, hence the need to rebalance the cells at each charging sequence.

On the other hand, when there are several cells in parallel it is difficult to determine the defective cell. Indeed, only the common voltage of each pack of cells in parallel is measured. Therefore, the parallel cell pack will be considered defective, even if only one cell fails.

The average failure rate of an accumulator λ (λ=1/MTBF where MTBF = Mean Time Between Failures) corresponds to the equation (1), with n the number of cells, whether in parallel or in series.

$$\lambda_{accumulator}\text{ (failure per hour)} = n \,.\, \lambda_{cell} \qquad (1)$$

So the probability R of not having the battery fail will correspond to the following equation:

$$R_n\left(\text{time}\right) = e^{-\lambda_{cell}.n.time} = R_{cell}^{n} \qquad (2)$$

Let consider a battery cell with an MTBF of 11,000 hours, with charge/discharge cycle daily. If there are 20 cells, the MTBF of the battery becomes 550 hours. The probability of not having a malfunction of the battery after 360 hours is 52% and after 720 hours is 27%.

In conclusion, the more cells there are, the more the reliability of the battery decreases. In addition, replacing a worn-out cell with a new cell in a battery that has already cycled a number of timese will cause balancing problems.

One solution consists of matching up battery cells but this requires time and skill. Battery manufacturing quality is crucial and the use of cells that have the closest possible characteristics can minimize problems.

In the estimation the reliability, the active or passive BMS must be taken into account, which further reduces the level of reliability. Battery maintenance calls for easy access and simple removal of each cell.

Finally, there are factors other than reliability which contribute to shortening the life of a battery.

What are the parameters which reduce the health status of a lithium battery?

4 Battery SOH and energy capacity

The energy capacity of a battery is given by the manufacturer. Figure 3 shows the variation of the energy capacity as a function of the temperature [5]. The the cut-off voltage for LiFePO4 is 2,50V.

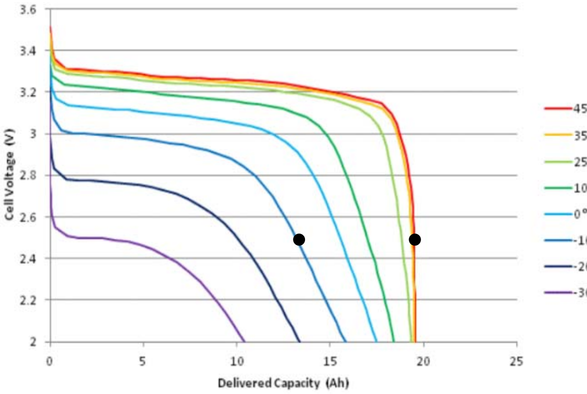


Fig. 3: Cell voltage vs. energy capacity for various temperatures(-30°C to +45°C), LiFePo4 discharge: 1C at 35°C, Q = 19.5 Ah.

In the figure 3, the voltage drop is mainly caused by the internal resistance of the battery which increases for temperatures below 10°C.

Following various tests, the value of the internal resistance of a healthy A123 20 Ah element corresponds to the equation (3):

$$R_{discharge}(T) = R_{45°C} + (R_{0°C} - R_{45°C}) \cdot e^{\frac{-T}{\tau T}} = 0.0015 + 0.01 \cdot e^{\frac{-T}{18}} \qquad (3)$$

The energy capacity Q of the battery as a function of the temperature corresponds to the following equations (4):

$$Q(A.h) = Q_{45°C} + (Q_{0°C} - Q_{45°C}) \cdot e^{\frac{-T}{\tau T}} = 19.5 + (16 - 19.5) \cdot e^{\frac{-T}{18}} \qquad (4)$$

The energy E provided by one element depending on the temperature corresponds to the following equation (5):

$$E(W.h) = 64.5 + (56 - 64.5) \cdot e^{\frac{-T}{18}} + \int R_{discharge(T)} \cdot I_{disch}{}^{2} \cdot dt$$

Aging mechanisms occur during the use of the battery (cycling aging) but also during the rest period.

For an A123, the depth of discharge between 0 and 80% (DOD: Depth Of Discharge) has very little influence on the charge status or health of a lithium battery [3], [4].

By contrast, a discharge beyond 100% (BMS “cut off” error), the elements short out irreversibly at 0 V with a low internal resistance. Moreover, in this state, “pouch” elements inflate, leading to the ability to diagnose these problems with (pressure?) sensors.

Statistics show that vehicles spend more than 90% of their lives in a car park, which proves the value of studying the non-negligible calendar aging mode. Moreover, one can see in the figure 4, the loss of energy capacity based on the number of cycles (Ah) and the discharge rate. This curve shows the aging caused by the charge and discharge cycle and by the calendar effect [4]. The C-rate is a measure of the rate at which a battery is charged or discharged relative to the capacity of the battery.

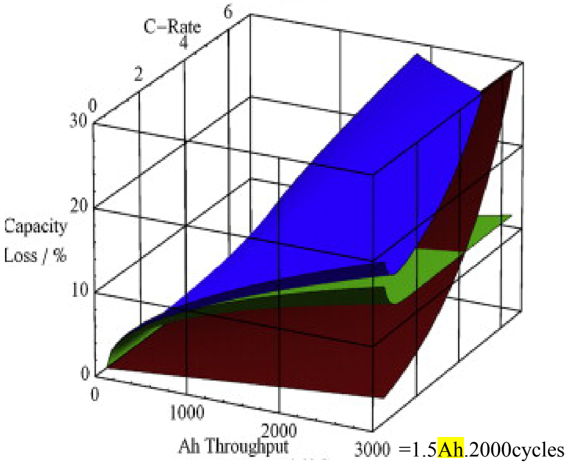


Fig. 4: Life Cycle Model vs. discharge (Ah) à 20° C for LiMn 1,5Ah 2000 cycles. Blue: loss of total energy capacity. Green: calendar loss. Brown: loss by discharge cycle.

This loss of capacity is partially caused by an increase in the internal resistance of the battery (ESR: Equivalent Serial Resistance) which depends on the temperature but also the depth of discharge as shown in the following figure in a healthy battery.

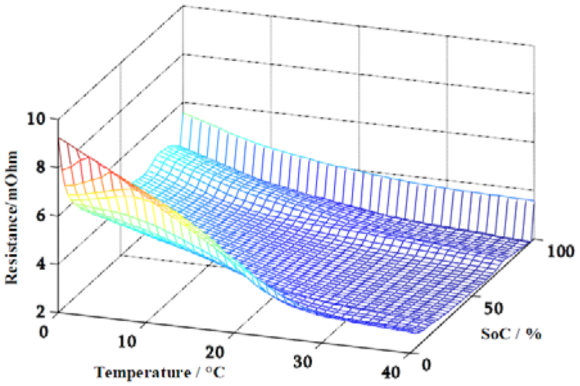


Fig. 5: Internal resistance during discharge vs. temperature and State of discharge –
Cell A123 LiFePo4 in healthy state [12].

At temperatures over 45 ° C, the calendar effect is more noticeable especially if the state of charge remains high.

The main cause of degradation mechanisms for lithium batteries causes the increase in the internal impedance Moreover, the aging effect is especially observed in the range [0.1 Hz, 1 Hz] of the real part of the internal impedance [3].

But how can be evaluated the health status of a lithium battery?

5 SOH measurement method

The state of health (SOH) of a battery is the energy capacity and the current it can provide without heating up (low increase of the temperature?): this condition therefore corresponds to a very low internal resistance. On a vehicle, it is necessary that the health and state of charge be known with an accuracy of about 1% to reassure the user.

Several methods exist for the calculation of SOH and SOC:

- The power integration method [10]: this is a count of the number of incoming and outgoing Watt-hours with a reset after each full charge. This method does not allow the determination of the relative changes in the charge state depending on the temperature, nor the determination of self-discharge, nor knowledge of the SOH at any given time.
- Direct methods based on measurements of the voltage and the internal resistance by pulses of charge and discharge [14] or of the dynamic impedance by spectroscopy. For LiFePO4, the variation of the voltage is very low in proportion to the depth of discharge (Figure 3), so this method cannot be used.

On the other hand, the method of estimating the internal resistance is often used. There are many ways that are dedicated to finding the SOC by the resistance:

- With dedicated integrated circuit like BQ27500 "battery fuel gauge".
- Using Adaptive Kalman filter methods: these are observer structures in which the correction is performed optimally and used to adjust the SOC.
- Measuring the constant current charging time (CC charge) and constant voltage (CV charge) [3]. These times clearly depend on the internal resistance of the battery and on temperature. But for this, we need a model of the variation of the internal resistance of the battery while charging, which will call for validation for several kind of load current (slow, fast), in each case according to the temperature. Figure 6 shows the charge time (CC and CV) of a healthy accumulator [10].

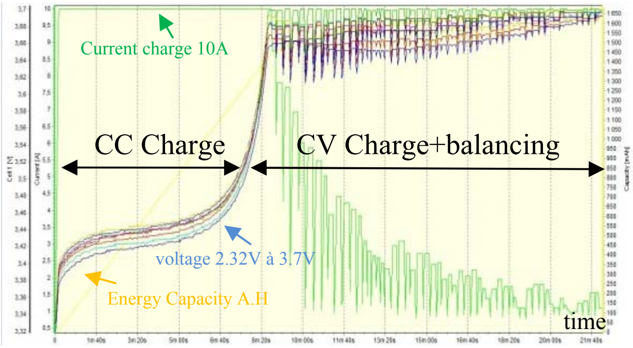


Fig. 6: Charging A123 20Ah cells at 0,5C in a healthy condition under 20°C with measuring the tensions of each cell vs of time.

We can observe in figure 6 that not all the cells are matched: there is not the same voltage on the different cell, whence the need to rebalance all the cells at each recharge.

For the bicycle electric vehicle, the power or current integration method is very easy to implement to check the consumption in Wh and battery health. So after a full charge, one can discharge at 100% until the "cut off" voltage of an element of the battery and finish the journey by pedaling. We must then verify that there are no significant differences with the other voltages of the battery elements and find out the energy capacity of the battery, i.e. its health for a given average temperature value of the battery.

After a 100% discharge, in other words at the BMS cut off point, during charging it is possible to measure the energy absorbed by the battery, with fairly good accuracy because the charging current is relatively low (charging rate of 0.25C to 1C) and therefore less sensitive to the value of the internal resistance of the battery. In addition, the load current is stable compared to the discharge current, which varies greatly. The battery power corresponds to the following equation:

$$E_B(W.H) = \text{mesurecharge}100\% - \int R_{\text{charge}(T,t)} \cdot I_{ch}(t)^2 \cdot dt \tag{6}$$

The charger measures the internal resistance every 2 minutes, as well as the integration of the battery power and the integration of losses in the resistance of the battery every 0.2s.

Example: After a 100% discharge at 25°C, i.e. when all the elements are at 2.5 V in a 21 cell A123 in series battery (1300Wh rated), a charge at 6 A gives a charging energy of 1310Wh, with the temperature rapidly increasing to 27°C. The resistance during the load is 4 mΩ, practically constant as a function of the DOD.

The energy of the battery approximately corresponds to the following equation:

$$E_B(T) = 1310 - \int_0^{\approx 3.15h} 21 \cdot 4 \cdot 10^{-3} \cdot 6^2 dt = 1300\text{Wh} \tag{7}$$

at 27°C

This 100% load energy is consistent with the usable discharge of 100%, less minor losses in the internal resistance, corresponding to the following equation (8):

$$E_B(W.h) = \text{measure}_{\text{charge}}100\% + \int R_{\text{discharge}(T,t)} \cdot I_{\text{dech}}(t)^2 \cdot dt \tag{8}$$

The relative state of health SOH of the battery corresponds to the following equation:

$$\text{SOH}(\%) = \frac{E_n(T) - E_B(T)}{E_n(T)} \tag{9}$$

where E_n corresponds to the nominal energy in the battery when healthy. E_n is given by the manufacturer documentation.

Consequently, the relative state of charge SOC can be determined by the following equation where E_B is dependent on the SOH (10):

$$\text{SOC}(\%) = \frac{E_B(T) - (\text{measure}_{\text{discharge}}100\% + \int R_{\text{discharge}(T,t)} \cdot I_{\text{disch}}(t)^2 \cdot dt)}{E_n(T)}$$

The SOH must always be re-estimated in the light of the use and temperature of the battery.

The internal resistance during charging is higher with respect to the resistance during discharge.

Therefore for a charge to 1C, the temperature reached by the battery is greater than during discharge [8], [12]. This explains why the maximum charge rate recommended by the manufacturer is only 1C for optimal lifetime. Knowing the health status of the battery of an electric car is more problematic because it is no longer drivable after a 100% discharge. But after a long journey, it is possible to finish fully discharging the battery at home, using the heater (about 5 kW for a car) and then fully recharge the battery to see the energy capacity of the battery at 100 % and the SOH.

But what is the allowable tolerance between cells?

6 Admissible tolerance between cells

For our electric cycles, battery life is defined by the limit at which the decline in performance is considered unacceptable. Generally, a loss of 25% of the nominal energy capacity marks the point beyond which the battery is no longer viable. In addition, heating above a critical value during a normal cycle of use is also a good indicator of failures. This critical value of the battery temperature is recommended by the manufacturer to maintain the insulator used in the cell and the electrolyte. For example, for an A123 20Ah cell, the maximum temperature of use is 60°C with a thermal resistance of 3°C/W of battery (with 1 mm space between the elements), a heat capacity of 800 J/°C and an entropy coefficient $dE(SOC)/dT$ which varies from -2mV/°C to 2mV/°C [5], [12] according to energy capacity. The temperature is measured on the positive electrode where the heat is greater than for the rest of the battery. Indeed, the positive terminal is made of aluminum which has a larger resistivity than the negative terminal (copper). The evolution of battery temperature corresponds to the following simplified equation:

$$(T - T_{amb})(°C) = P(W) \cdot R_{TH} \cdot (1 - e^{\frac{-t}{R_{TH} \cdot C_{TH}}}) \qquad (11)$$

The power lost in the battery element corresponds to the following equation, with R(Ω) corresponding to the internal resistance of an element and I(A) to its intensity.

$$P(W) = R(T,SOC) \cdot I^2 + I \cdot T \cdot \frac{dE(SOC)}{dT} \qquad (12)$$

<u>Example:</u> For a continuous discharge at 2C rate, i.e. at 40A, with an ambient temperature of 20°C and a resistance of 2 mΩ, the cell will have a power to dissipate of 3.2 W. Therefore, the temperature increase will be 6.4°C which is not a problem for the cell. However, if the internal resistance increases to 12 mΩ due to aging, then the dissipated power reaches 19.2 W and the increase in temperature is 38.4°C so 58.4°C across the electrodes with an ambient temperature of 20°C. This temperature is critical and the BMS will stop the operation of the vehicle if there is no forced ventilation of the battery. In figure 7, we can observe the evolution of heat loss of an element depending on the depth of discharge and time.

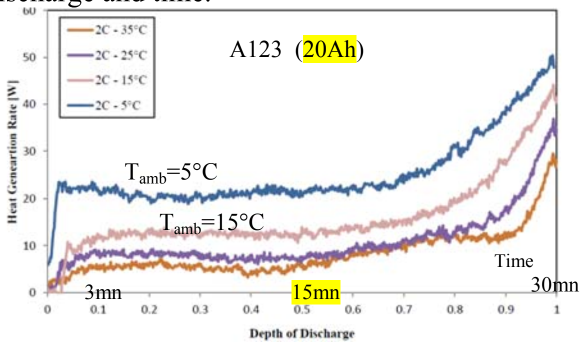


Fig. 7: Heat loss for different ambient temperatures for a 2C discharging current vs time or DOD.

Moreover, the increase in temperature will be greater at 5°C than at 35°C because the internal resistance is greater at low temperatures. In the figure 8, we can observe the increase in temperature for a large discharge rate of 4C. At 5°C ambient temperature, the battery temperature reaches an optimum operating temperature of about 20°C. Energy loss caused by the internal resistance of the battery to a 100% discharge corresponds to the following equation:

$$W_{loss}(W.H) = \int_0^{t_{100\%}} R(SOC,T) \cdot I^2 \cdot dt \qquad (12)$$

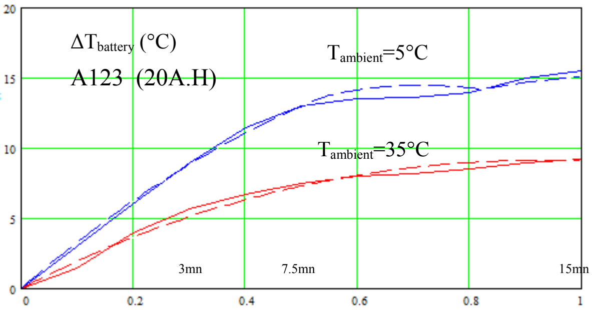


Fig. 8: Heat increase for a discharge current 4C based on the DOD and time in healthy, measured in solid line and dotted line modeled.

At an ambient temperature of 20°C, for an A123 64 Wh cell in healthy condition with a resistance of 2 mΩ, the energy lost is 0.8 Wh at 1C and 1.6 Wh at 2C, corresponding to 2.6 % of the rated capacity. In degraded mode, with a resistance of 12 mΩ, the energy lost is 4.8 Wh at 1C and 9.6 Wh at 2C, corresponding to 16% of the rated capacity.

It can be noticed that an internal resistance difference causes a longer recharging time at constant voltage because of the balancing of each element.

The increase of 100% of the nominal resistance causes the battery replacement.

7 Charge balancing

If all the electrochemical voltages (OCP: Open Circuit Voltage) are identical, then the rebalancing time in each cycle only depends on the difference in internal resistance between the cells with the highest and lowest values, called ΔR. This load balancing time t(h) depends on the power during the balancing and corresponds to the following equation:

$$t(H) = \frac{\Delta E_{balance}(W.h)}{power_{charge\_1\_cell}} \qquad (13)$$

Where $\Delta E_{balance}$ corresponds to the difference of the energy loss in the resistors and is given by (14):

$$\Delta E_{balance} = \int \Delta R_{discharge} \cdot I_{disch}{}^2 \cdot dt + \int \Delta R_{charge} \cdot I_{ch}{}^2 \cdot dt$$

In the worst case, with a discharge at 2C and a 1C charge, with a 100% discharge, the out-of-balance equation is as follows, with the energy capacity Q(Ah) and a 1C charge rate:

$$\Delta E_{balance} = (\Delta R_{discharge} \cdot I \cdot 2 + \Delta R_{charge} \cdot I) \cdot Q \qquad (15)$$

In the case of the A123 20Ah battery, a current of 20 A with 1 mΩ difference in resistance between the discharge and the charge, the energy difference will be 2 Wh.

With 1.65 W of power for balancing for a cell, it will take 1.2 hours to complete the rebalancing.

Passive low-power balancing, discharging the most loaded cells with resistances, is an inexpensive solution to implement. This kind of balancing can be seen in Figure 6. On the other hand, an active rebalancing may be faster, but this system is more complex and therefore more expensive.

If rebalancing is not done, then the difference in energy capacity between the cell that has the lowest internal resistance and the element that has the highest will increase. So the energy capacity of the battery will be lower.

The SOH and the SOC should be determined with regard to the rebalancing and as a function of the element which has the highest discharge resistance.

Electric vehicle instrumentation indicates to the user: the consumption in Wh, the % of energy remaining, the temperature of the battery cells, the Wh per km...

The instrumentation used [10] has a 0.12% power measurement error and an error on the energy measurement of 0.124%.

Apart from knowledge of the battery's state of health, of the energy drawn from it in real time, what interests the user of an electric vehicle is the number of kilometers that can still be covered with the remaining energy.

In all cases, the distance will depend on the consumption of the vehicle and the ground to cover. That's why an energy-use estimator based on the sum of elevation gain and loss and on average speed was developed.

8 Consumption estimate in motion

Since 2012, an ebikemaps.com implementation [11] has been developed to estimate the consumption of an electric vehicle.

This means that it is now possible to trace one's route on "Google Maps" and find the elevation gain and consumption involved. For this, the vehicle must be modeled with the aerodynamic coefficient k_{aero} $(W/(km/h)^3$, the rolling coefficient k_{roll} and the efficiency of the motor η in relation to its resistive power. The power consumption of the vehicle [10] corresponds to the following equation (16).

$$P_{abs}(W) = \left[k_{Aero} \cdot Speed^3 + (k_{roll} + k_{slope}) \cdot Speed(km/h) \right] / \eta$$

On a given route, the energy consumption as a function of the vehicle can be roughly estimated by the following equation (17):

$$E(W.h) = (P_{motor}(Speed) - P_{human}) \cdot \frac{(distance - D^-)}{Speed_{average}(km/h)} + \frac{M \cdot g \cdot D^+}{3{,}6} \qquad (17)$$

with the average speed in km/h, D +, D- positive and negative elevations and distance in km.

From the above equation, an estimation of the battery's energy consumption can be achieved, as can be seen in the following figure with its battery meter depending on the route, the average speed and the outside temperature.

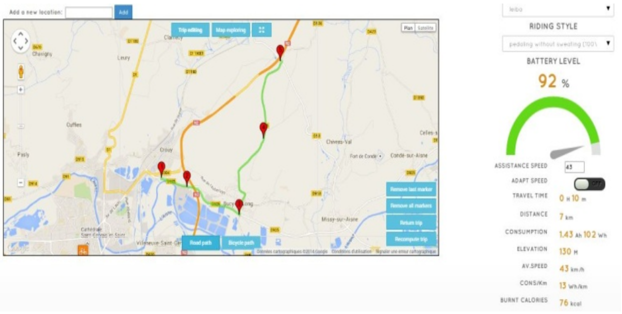
The accuracy of the estimation is about 5% on trips between 20 and 200 km.

About 50% of consumption depends on the amount of climb with vehicles that have a small mass of about 140 kg, cyclist included. It should be remembered that the estimator does not take into account the electric regenerative braking, the particle size of the road, the wind and any consumption due to acceleration.

It may be noted in Figure 10 that the power varies greatly with the frequent accelerations on a trip, while the estimator smooths out these energy demands. One gauge on a particular electric vehicle shows the distance that can still be covered using the following equation, with the remaining battery capacity and the average consumption over a certain distance (in this case 10 km) (18).

$$Distance(km) = capacity_{residual}(W.H) / \left[consu_{average}(W.H) / 10km \right] \qquad (18)$$

From this equation, the estimated remaining distance will be distorted if a slight downhill stretch is followed by a steep climb. The average consumption of the e-bike can thus rise from 5 Wh/km to 10 Wh/km on some routes for the same average speed because of the route profiles. The application [7] indicates the true remaining distance from the desired destination.



pedaling without sweating (100\
ASSISTANCE SPEED 43
ADAPT SPEED OFF
TRAVEL TIME 0 H 10 m
DISTANCE 7 km
CONSUMPTION 1.43 Ah 102 Wh
ELEVATION 130 M
AV.SPEED 43 km/h
CONS/Km 13 Wh/km
BURNT CALORIES 76 kcal

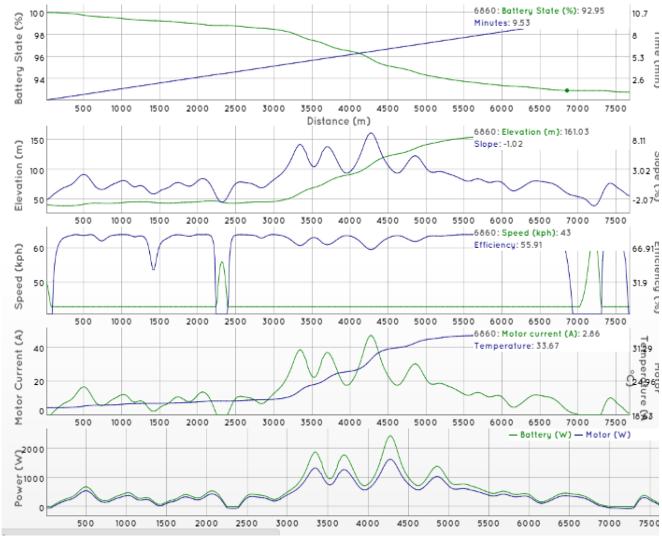


Fig. 9: Estimation of energy consumption based on a journey and an average rate fixed for a streamlined tricycle. The resistive power and motor temperature are also estimated.

In the figure 10, the measurements for consumption and power on the previous journey can be seen, which provides confirmation of the estimator.

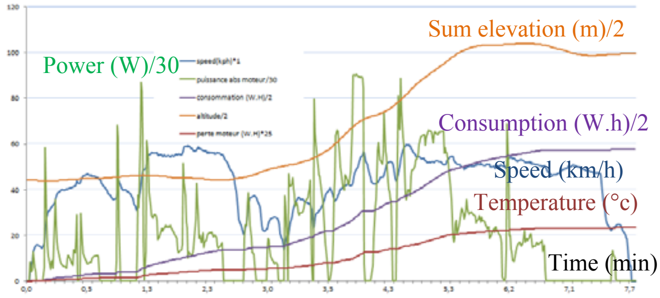


Fig. 10: Recorded speed (blue), power (green), energy (purple), altitude, the amount of vertical gain and engine temperature.

9 Estimating battery lifetime

On the A123 20 Ah batteries at 25°C, the calendar aging causes a loss of less than 3% of the energy content over 15 years, as can be seen in Figure 12 estimated by the manufacture.

In Figure 13, the number of cycles at 25 ° C is 5200 cycles (102600 Ah) for a loss of 20% of the energy content relative to the initial capacity. Since the velomobile consumes about 1200 Ah per 10,000 km, the estimated lifespan of the battery is 850000 km with a 2C discharge current, at a temperature of 25°C and a 100% discharge rate.

In general, 90% of cycles have shallow discharges below 40%. But manufacturers rarely give the equation or the curve of the number of life cycles based on the DOD such as can be seen in the figure 13 [5], [13].

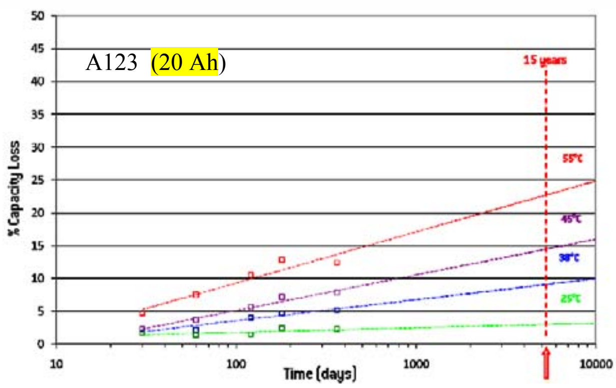


Fig. 11: A123 20 Ah LiFePo4 calendar aging of items with 50% stored energy [5].

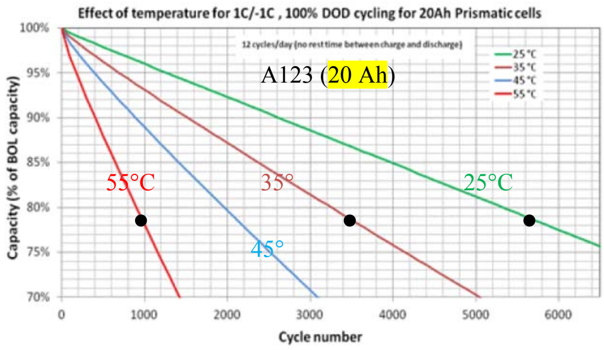


Fig. 12: Loss of energy capacity at different temperatures with 100% DOD.

Figure 13 shows the energy capacity exchanged (cycle of consumption) into Ah depending on DOD. One can observe that there is an optimization around 37% of DOD.

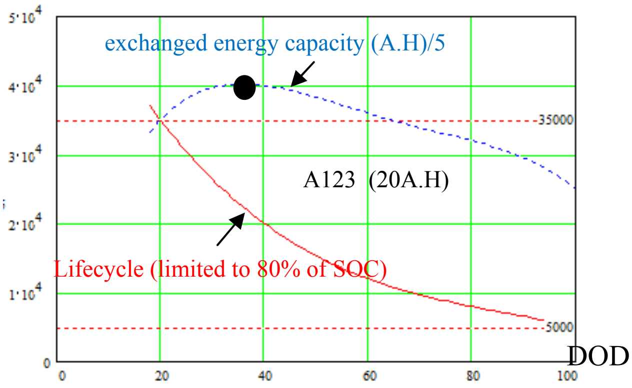


Fig. 13: Evolution of the number of cycle and consumption exchanged Ah according DOD at 25 °C with everyday use.

10 Conclusion

This article has shown that it is possible to establish the health status of each element of a battery on an electric vehicle.

The increase of the internal resistance due to aging causes a drop in the energy capacity as well as a heating detrimental to the battery. Meanwhile, the lifetime depends on the rate of discharge and the storage temperature. Therefore, for a given power, it is preferable to increase the battery voltage to not exceed a 2C discharge rate. This increase in the voltage application requires a greater number of elements with a consequent drop in reliability. To minimize the discharge rate, the use of supercapacitors is a solution [6], but for the time being this is still expensive. Knowledge of the aging of the battery as a function of its use can lead to an estimation of its lifetime for a marketing study [3]. Establishing the possible number of cycles for a battery requires relatively long studies. This data is rarely provided by manufacturers. It is the same for the reliability of the cell. In all cases, the range will depend for the major part on the vehicle's consumption.

For all these reasons, a consumption estimator is vital to take into account the sum of the elevation differences, average speed and outside temperature. An application has been successfully tested on over 1500 cycles (bicycles, tricycles, velomobiles). This estimator also takes into account the health status of the battery and its temperature, which plays an important role regarding the energy capacity of the battery. This estimator is an effective range management strategy that can be used for all types of electric vehicles.

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