USING WIRELESS CHARGING TO PROLONG LEAD-ACID BATTERY LIFETIME

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Abstract. This article analyses the impact wireless charging can have in prolonging lifetime of lead-acid batteries used in slow-moving electric vehicles. A Simulink model was created to simulate deterioration of battery state of health at various charging scenarios. The simulation results show possibilities of significant lifetime increase of up to four times if using en-route wireless charging to optimise charging schedules, which makes using wireless charging cost-effective solution.

Keywords: wireless charging, electric vehicles, lead-acid batteries, battery lifetime.

Introduction

Since signing of the Paris Agreement the importance of decreasing greenhouse gas emissions has become more acute as ever, and to achieve the set goals of holding the increase in the global average temperature to well below 2 ºC above pre-industrial levels [1] one of the most problematic areas will be transport, as it is the only major sector in the EU where greenhouse gas emissions are still rising [2].

With electric vehicles as a viable solution to CO_2 emissions becoming more and more commonplace, most of attention is being focused on increasing the lifetime of lithium chemistry batteries, sometimes quite undeservedly forgetting that there is still a wide range of applications for more traditional battery chemistries like lead-acid batteries.

One of such areas where lead-acid batteries are still used more widely than any other chemistry is slow-moving electric motor vehicles. Slow-moving vehicles include variety of electric vehicles, including neighbourhood electric vehicles for golf and tourism, their driving speed does not exceed 50 $km \cdot h^{-1}$, and the engine power of these vehicles is within a range of 1-5 kW, with driving distance around 40-75 km[3]. The use of lead-acid batteries in these vehicles is justified by their low costs and lack of necessity for high energy density.

The lead-acid battery industry is actively working on improving operational parameters of lead-acid batteries replacing traditional lead-acid batteries with advanced lead-acid batteries, by introducing new additives (like calcium, aluminium), congealing electrolyte, like in absorbent glass mats (AGM) or silica gel batteries, and working on overall design improvements, like tubular plate design or prismatic cells. All these efforts have lead to prolonged battery lifetime and improved ease of the operations [4].

Nevertheless, improvement of the manufacturing process and product parameters is just one way of prolonging the battery lifetime; another is to decrease the impact of operational factors that leads to deterioration of a battery during its service, in particular charging scheduling. This is not a widely examined direction, because as a rule it is accepted that charging schedules are invariable – they depend on the particular use of the vehicle and cannot be changed. However, with introduction of wireless charging, this is no longer true – introducing en-route wireless charging can bring additional economic benefits, not just ease of use.

The present paper aims to demonstrate how wireless charging can prolong the slow-moving vehicle battery lifetime and what positive economic impact this would bring to the vehicle owners.

Materials and methods

In order to evaluate the possible effects of wireless charging, a simplified battery degradation model was created in Matlab Simulink.

The block diagram of the structure of the model is shown in Figure 1. Pre-set parameters of the electric vehicle and its use determine the charging and discharging process and remaining battery charging cycles.

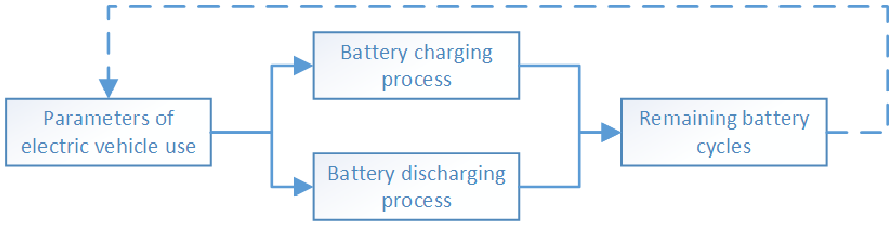

Fig. 1. **Structure of the model**

The main difference between wired and wireless charging lies in the possibility to add charging en-route, which is especially useful in the case of slow-moving EVs, as they are mostly used in applications with predetermined and often cyclical route.

In the model developed for this research data from Melex 963DS electric vehicle, which is used to carry tourists around gardens of Rundale palace in Latvia in summer months from May to September, were used.

The route is approximately 3 km long and takes about 20 minutes with 10 minutes between rides. Currently the vehicle is charged once a day during night (see Figure 2). By introducing wireless charging at the passenger loading station it becomes possible to charge the vehicle several times a day, so that to keep battery state of charge (*SoC*) in 60-80 % level (or depth of discharge (DoD) at 20-40 % level).

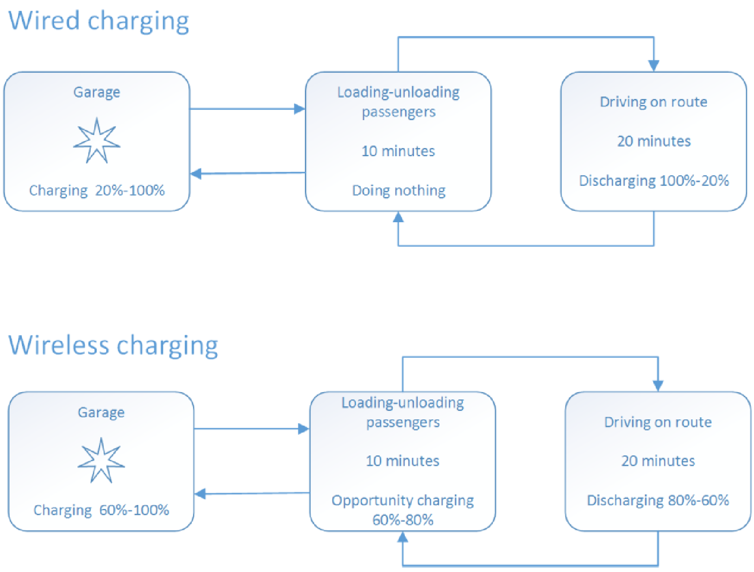

Fig. 2. **Wired vs. wireless charging schedules**

For the simulation average Melex 963 operational parameters were used, as determined in the test drivein the previous research by Berjoza et al. [3]:

- battery capacity: 240 Ah, 48V, 11.52 kWh;
- average discharge: 0.2 $kWh \cdot km^{-1}$;
- average speed: 9 $km \cdot h^{-1}$;
- built-in charger 30 A, 48 V, 1.44 kW;

Electric vehicle is using six U.S. Battery US 2200 XC2 type or Trojan Battery Company T-105 type batteries connected in series. The battery charging characteristics obtained experimentally are shown in Figure 3.

Based on these data, equation explaining the battery state of charge (%) dependence on charging time (in minutes) was developed (Figure 4) – a sigmoid function (1) with R^2 = 0.9992:

$$SOC = \frac{2}{\exp\left[\frac{-t}{80 \cdot \exp\left(\frac{-t}{200}\right) + 120}\right] + 1}. \quad (1)$$

Correspondingly the SoC growth function (% charged) in one period (minute) (2) was estimated with regards to the previous status of SoC_t, using equation (2)

$$\Delta SoC(t) = -0.0095 \cdot SoC_{t-1}^3 + 0.0079 \cdot SoC_{t-1}^2 - 0.0095 \cdot SoC_{t-1} + 0.0026 \quad (2)$$

The graph showing SoC growth is presented in Figure 5. It shows good correlation with experimental observations – $R^2 = 0.9944$.

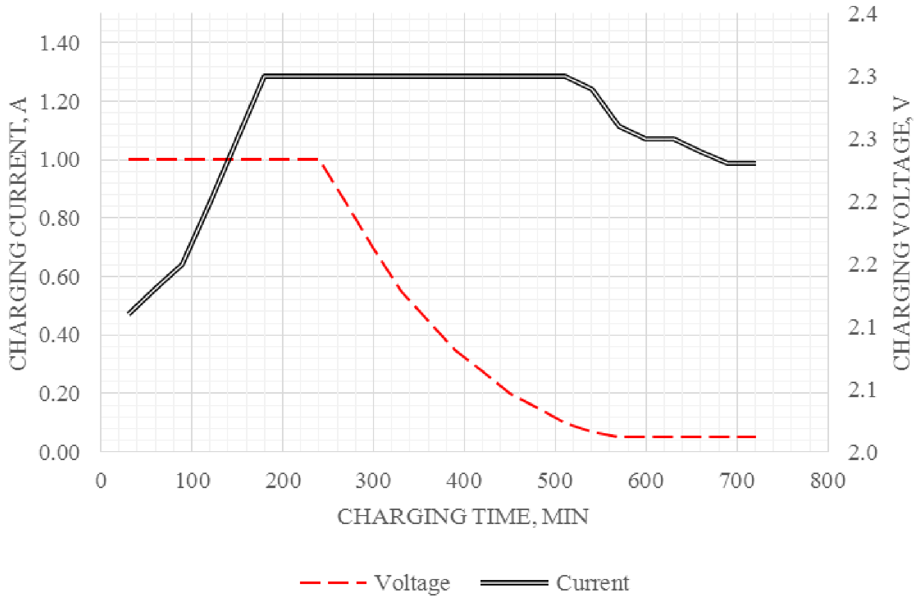

Fig. 3. **Experimental results of battery charging voltage and current experiments**

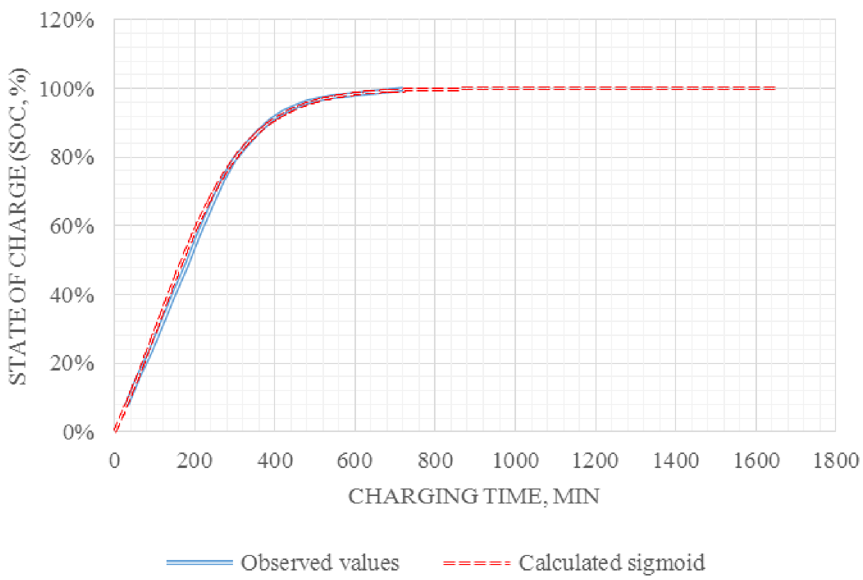

Fig. 4. **State of charge depending on charging time**

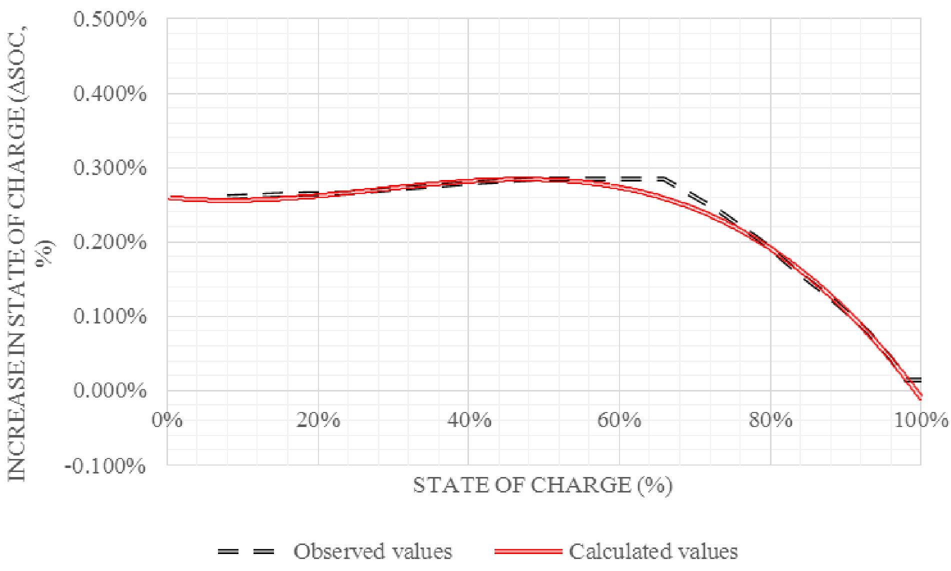

Fig. 5. ***SoC* growth function (R^2 = 0.9944)**

In lead–acid batteries, major aging processes, leading to gradual loss of performance, and eventually to the end of service life, are anodic corrosion, positive active mass degradation (shedding, sludging), formation of lead sulphate in the active mass (sulphating), mechanic defects (short-circuits) and electrolyte degradation (stratification) [5].

Partly consolidated version of the causal tree analysis of depth degradation of the lead acid battery (Figure 6) created by Kais Brik and Faouzi ben Ammara, which depicts the factors and their influence on the battery lifetime [6], was used for model development.

In creating the model, the black box principle was applied; process inputs and outputs for factors influencing the battery lifetime without going into complex mechanics of why and how they happen were used. Also it was assumed that most technical factors related to the battery charging process are unrelated to the energy transfer method, therefore, only the factors that directly can be affected by removal of charging wires – respectively depth of discharge (*DoD*), are coloured-in and subsequently used in our model.

Several battery aging models are used in research to determine the number of charging cycles: e.g., equivalent full cycles to failure method defines the end of the battery lifetime when a specified number of full charge–discharge cycles are reached. The battery manufacturers' data on battery cycle life *N*(*EoL*) dependency on the depth of discharge (*DoD*) [7] are presented in Figure 7, which corresponds to equation (3) with R^2 = 0.999.

$$N(EoL) = 519.22 \cdot DoD^{-1.137} \tag{3}$$

One of the decisions that has to be taken before creating the model is what constitutes the state of battery health when it can be considered faulty. Battery standard EN 60896-11:2003 defines the end of the battery lifetime when the potential battery capacity falls below 80 % of nominal capacity [8]. This can be also observed in battery use: if possible, the users tend to choose the battery size according to their needs with a small (20 %) margin, hence, if the battery capacity falls below those 80 %, the battery can be considered unusable (failed), because it is not enough to fulfil the purpose. However, because by introducing wireless charging we have added a possibility of charging en-route, the current definition of battery end of life for comparison purposes is no longer valid – to fully understand the difference we have to use a more general definition: battery end of life is when it is no longer suitable to fulfil the minimum requirements of its use.

Thus, we have to give up conventional simple life cycle determination methods and use more general methods. At first we standardized the battery lifetime. By assuming that as cycles to failure N(EoL) correspond to 20 % of nominal capacity, we recalculated the impact of one full charge/discharge on battery capacity (‱) at various *DoD* levels Z_{full} (Figure 8a).

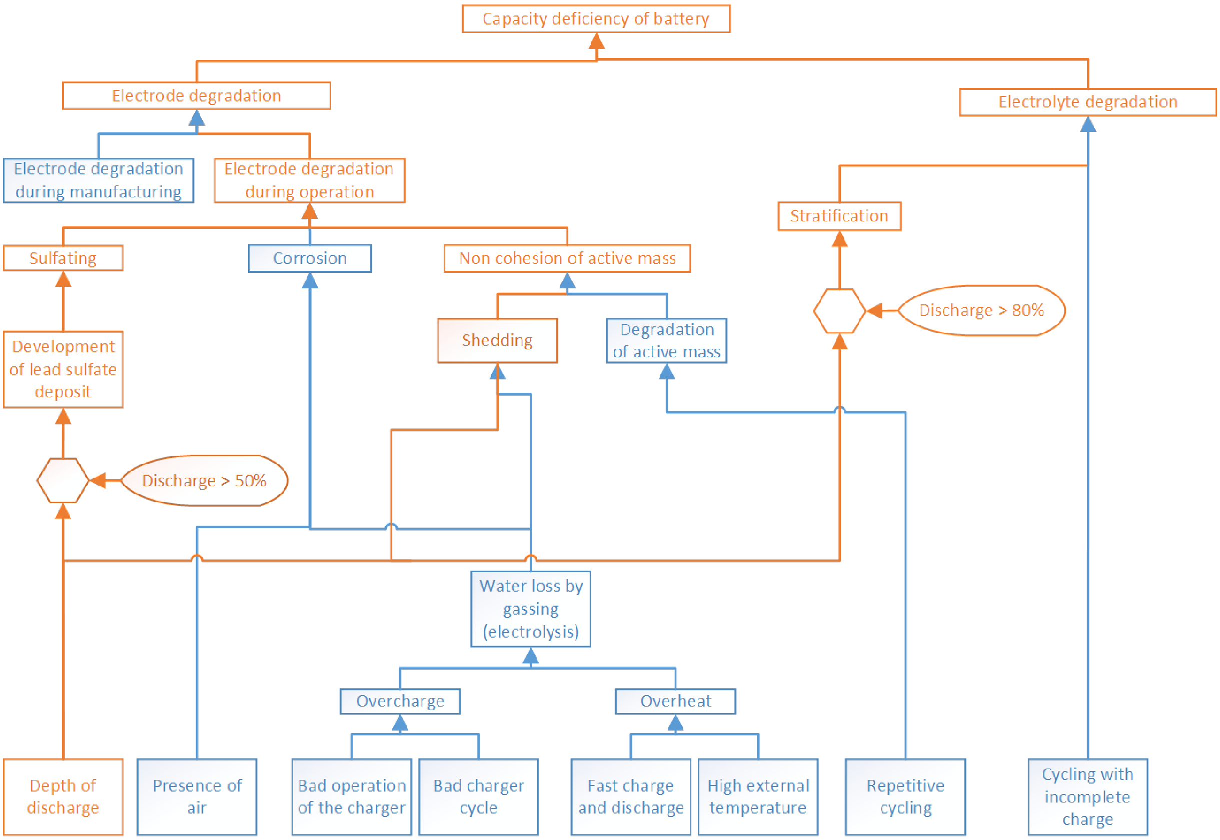

Fig. 6. **Causal tree analysis of DoD impact on capacity deficiency of battery**

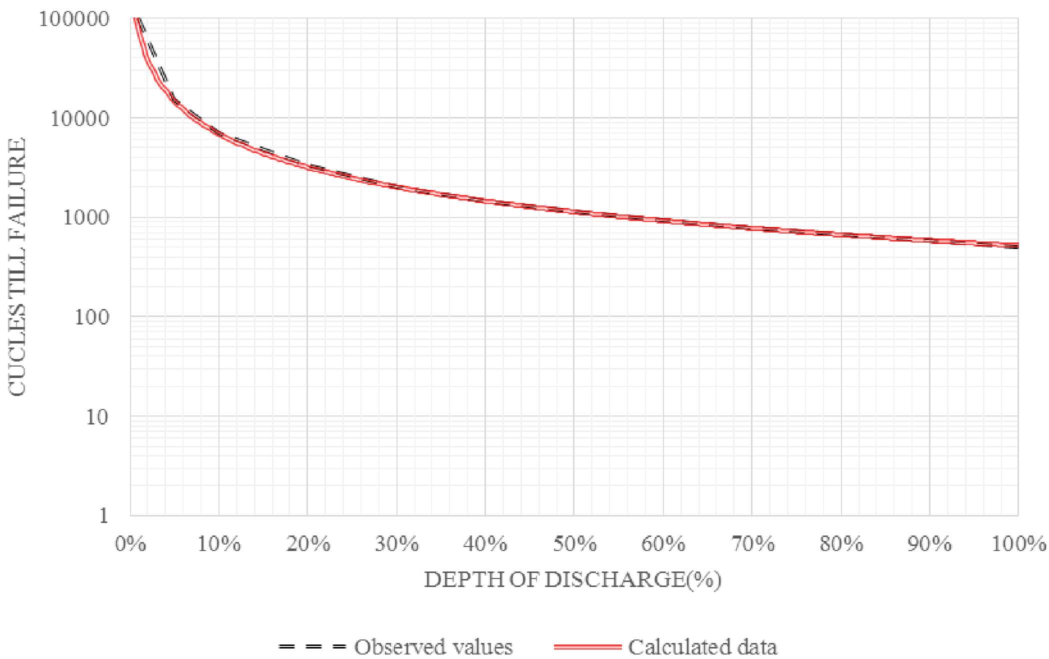

Fig. 7. **Cycles till battery failure depending on *DoD* (R^2 = 0.999)**

However, as not all charging/discharging happens at full cycles, we make an estimation of impact of 1 % (of nominal battery capacity) charging/discharging cycle on degradation of the actual battery capacity $Z_{1\%}$ by dividing Z_{full} with *DoD*. (See Figure 8B) The resulting formula in (basis points) is shown in (4).

$$Z_{1\%} = \frac{Z_{full}}{DOD} = 0.038519 \cdot DOD^{0.137} . \qquad (4)$$

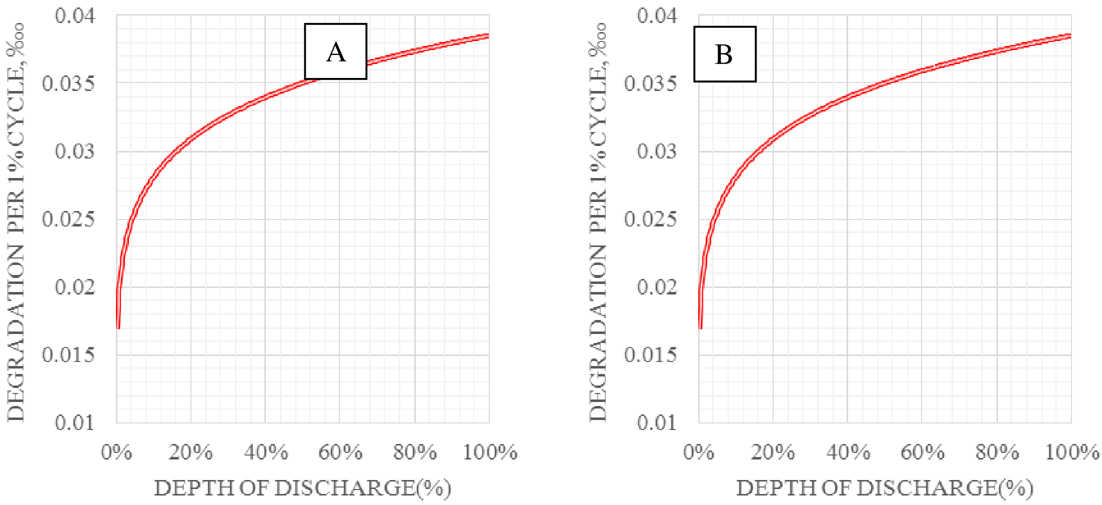

Fig. 8. **Degradation of battery capacity:** a – basis points per full cycle;
b – basis points per 1 % charge cycle

The Simulink model was developed based on the above mentioned equations (1-4) and simulation model structure (see Figure 1). Due to complexity and the size the visual image of the model is not presented in the article. This model is used to simulate various electric vehicle charging and driving scenarios to find out if there is a difference in battery lifetime.

Results and discussion

The total amount of energy charged and discharged in both scenarios remains the same, the only difference being added convenience of wireless charging during operation (see Fig. 9).

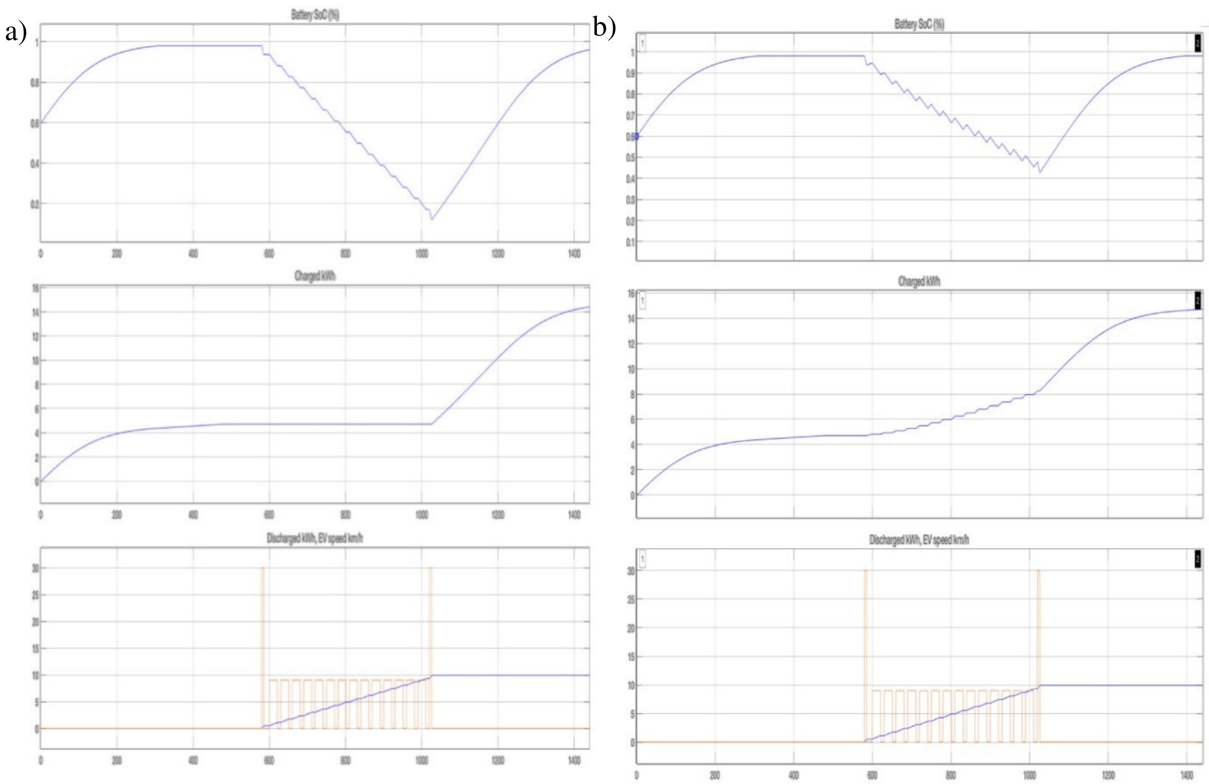

Fig. 4. **Charging parameters with ordinary charging(a) vs. wireless charging (b)**

However, because of different battery *SoC* during charging, the battery deterioration is quite lower during wireless charging than during ordinary charging (see Figure 10).

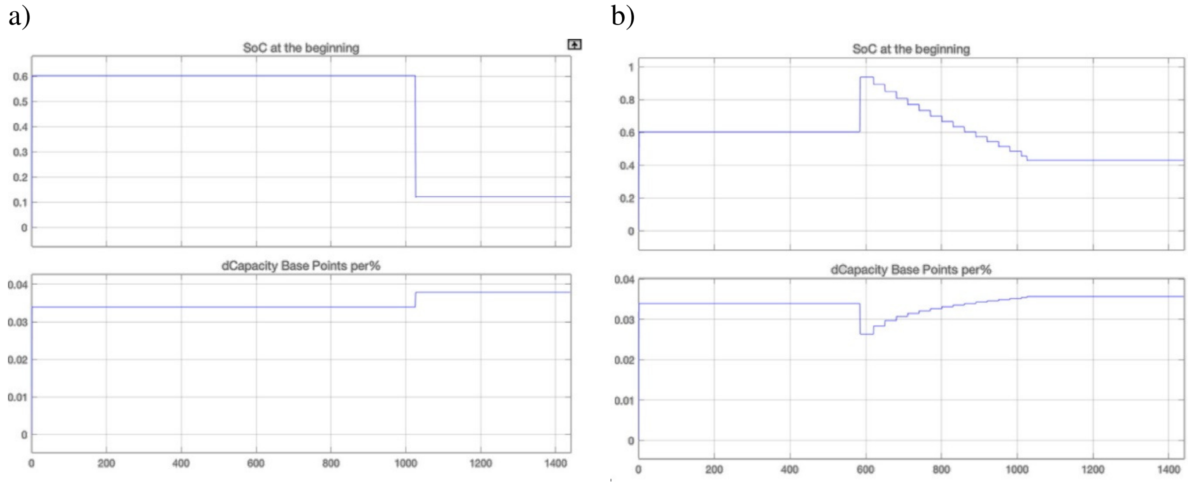

Fig. 5. **Capacity loss during charging at ordinary (a) vs wireless (b) charging scenarios (basis point per per cent charged)**

In a standard charging scenario, a battery loses122.25 basis points of its nominal capacity in a month, and at the classic failure margin of 20 % the expected battery lifetime to failure is 14.97 months.

Yet, at the simulated driving route the maximal *DoD* is 88.1 % and the corresponding minimal battery capacity to be able to carry out the task is 10.15 kWh, hence margin to failure is only 12 % and the expected battery lifetime to failure is 8.9 months. This corresponds with the actual usage data – on average batteries in this particular route are used for two seasons (lasting from May to September).

In a wireless charging scenario, a battery loses 122.25 basis points of its nominal capacity in a month. At the classic failure margin of 20 % the expected battery lifetime to failure is 16.36 months, or an increase of 9 % over standard charging.

However, the maximal *DoD* is 57.2 % and the corresponding minimal battery capacity to be able to carry out the task is 6.6 kWh, hence margin to failure is 42.6 % and the expected battery lifetime to failure is 34.88 months, or almost 4 times as much as in the standard charging scenario.

Hence, the users can either use their batteries four times longer (8 years instead of 2 years) or they can purchase fewer batteries at the first place to optimise costs. A standard 240 Ah battery pack for Melex 963 costs around 1500 EUR. If an ordinary charger costs 300 EUR and a wireless charger costs 1500 EUR, the average battery costs in 8 year period will be 770 EUR a year if using the standard charger and only 412 EUR a year using the wireless charger.

Conclusions

1. The model showed that battery lifetime can be prolonged by using wireless changing and that the lifetime increase is around 9 % in this particular example.
2. The biggest effect however comes from the possibility to use batteries longer than with ordinary charging by applying optimised charging schedules. The expected battery lifetime almost quadruples in this particular example.
3. The financial effect from using batteries longer or to buy fewer batteries at the first place more than compensates for the differences in the price between ordinary and wireless chargers making wireless charging a financially sound solution.

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