Kostopoulos, Emmanouil D.; Spyropoulos, George C.; Kaldellis, John K.

Article

Real-world study for the optimal charging of electric vehicles

Energy Reports

Provided in Cooperation with:
Elsevier

Suggested Citation: Kostopoulos, Emmanouil D.; Spyropoulos, George C.; Kaldellis, John K. (2020) : Real-world study for the optimal charging of electric vehicles, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, pp. 418-426,
https://doi.org/10.1016/j.egyr.2019.12.008

Energy Reports 6 (2020) 418–426

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Real-world study for the optimal charging of electric vehicles

Emmanouil D. Kostopoulos [a,*], George C. Spyropoulos [a,b], John K. Kaldellis [a]

[a] Mechanical Engineering Department, University of West Attica – Campus 2., P.Ralli & Thivon Avenue 250, Aigaleo 12244, Athens, Greece
[b] Laboratory of Climatology and Atmospheric Environment, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, Panepistimioupolis Zografou 15784, Athens, Greece

ARTICLE INFO

Article history:
Received 15 October 2019
Received in revised form 21 November 2019
Accepted 9 December 2019
Available online xxxx

Keywords:
Electric vehicles
Energy losses
Optimal charging procedure
Real-world experiment
Second life battery market

ABSTRACT

Electric Vehicles (EVs), accompanied with the use of Renewable Energy Sources (RES), are the solution for the decarbonization of the transport sector and are undoubtedly on the rise. Although EVs have been in the limelight over the last decade, little effort has been made towards the proper use of the vehicle's battery. Therefore, a better understanding of Lithium-ion (Li-ion) batteries, since they represent the heart of the majority of electric cars, during the discharging and charging procedure is crucial. The present study, that was experimentally conducted under real-world driving conditions, quantitatively analyzes the energy losses that take place during the charging of a Battery Electric Vehicle (BEV), focusing especially in the previously unexplored 80%–100% State of Charge (SoC) area. The results show that losses, during charging within the abovementioned area, are almost double compared to the 20%–80% SoC area and vehicle's average specific real energy consumption is almost 2 kWh/100 km more, compared to what the driver sees on the EV's dashboard. Furthermore, it is not for the driver's benefit to exceed 80% of SoC during charging, considering the required charging time, the distance that each SoC area provides and the life expectancy of the battery itself. Based on these results and after a thorough literature review, the authors suggest the optimum SoC range within which drivers should operate the EV's battery.

1. Introduction

The importance of decarbonizing the transportation sector lies in the fact that it is the second largest CO_2 emitter following the energy generation sector being responsible for almost 23% of global CO_2 emissions (International Energy Agency (IEA), 2016). More precisely, during 2016, the road transport was responsible for 72% of total greenhouse gas (GHG) emissions of the sector in EU-28 (European Environment Agency (E.E.A.), 2018). Driven by EU policies and CO_2 reduction targets, EV's market have seen an unprecedented growth with the EV global sales to climb from 1.2 million in 2017 (International Energy Agency (I.E.A.) and Organisation for Economic Co-operation and Development (O.E.C.D), 2018) to 2.1 million in 2018 (Irle, 0000) (Fig. 1). Although there are several challenges for the adoption and development of the electric car industry, most of them are originated to EVs' batteries themselves. Since the battery of any BEV represents almost 75% of its drivetrain cost (Berckmans et al., 2017), it is obvious why the biggest issue that EVs are facing is their high purchase cost. Although forecasts (Kane, 2018; Carrington, 2016) expect the average price of Li-ion battery packs to fall from $200-$250 per kWh, which ranges today (International Energy Agency (I.E.A.) and Organisation for Economic Co-operation and Development (O.E.C.D), 2018), to $100/kWh by 2025, the importance of maintaining EV's battery in a good condition, not only to resell the car in a good price but also for second-life applications, could help reduce both the battery cost for EV manufacturers and the purchasing cost for EV customers (Jiao and Evans, 2016).

The main objective of this study is to experimentally investigate EV's battery behavior during charging and to quantitatively define potential energy losses. Another goal is to prove that EV manufacturers should develop a battery management system (BMS) that will optionally limit the discharging–charging procedure virtually between 20% and 80% of SoC respectively, which represents the SoC area within which a Li-ion battery should operate. More precisely, as Mishra (2018) stated, EV's battery must operate within a safety zone rather than taking advantage of the full range between 0% and 100%. Many studies have been conducted that conclude to a minimum level of discharging around 20% and a maximum level of charging between 80% and 90%. Other authors (Schoch et al., 2018) have mentioned that a beneficial battery cycle should have a low Depth of Discharge (DoD) of 20%, partly agreeing with Dai et al. (2013), where a SoC ranging between 10% and 90% is suggested. On the other hand, in order for EV users to exceed the given battery warranty,

* Corresponding author.
E-mail address: emkostopoulos@uniwa.gr (E.D. Kostopoulos).

https://doi.org/10.1016/j.egyr.2019.12.008

other studies (Battery University, 2016b) suggest that new EV batteries should have a discharging–charging rate between 30% and 80%. Additionally, it is recommended not to exceed a SoC of 80% during charging (Eider and Berl, 2018), since it is a desirable operating target (Drouilhet and Johnson, 1997) and therefore – for battery health reasons – a SoC window of 20%–90% is preferable to use (Marra et al., 2012).

Jiang et al. (2014) and Lu et al. (2013) have conducted an in-depth research, on how different SoC ranges affect Li-ion's battery capacity degradation. When battery is cycled in a SoC range below 25% and above 75% the fastest capacity fade occurs, while an early termination around 80% of rated capacity is activated. Particularly, Lu et al. (2013) resulted that by discharging and charging Li-ion batteries following the abovementioned pattern, their internal resistance increases rapidly which lead to capacity fade. On the contrary, both researches proved that batteries that operate between 20% and 80% of SoC, present excellent cycling performance with essentially reduced capacity degradation. Therefore, in the current study the lowest level that the car will be discharged is that of 20% of SoC. Although the upper level of charging is that of 100% of SoC, due to the abovementioned reasons combined with the unexplored area beyond 80% of SoC, the investigation of the charging process will be split into two stages. The one concerns the 20%–80% of SoC area and the other the 80%–100% of SoC area.

Continuously operating the EV's battery below 20% and beyond 80% of SoC has been proved very harmful and dangerous as well. According to Safari (2018) and Guo et al. (2016), several degradation phenomena are occurred during the fully discharged procedure. Namely, Li-ion's lifespan declines over time, structural degradation and dissolution of active materials and thermal runaways might happen. Also, Fernandez et al. (2013) mentioned that operating Li-ion batteries outside the safety zone (i.e. 20%–80%) a loss in conductivity can be observed. Concerning safety issues Li et al. (2001) and Wu et al. (2015), noted that overcharging can reduce lithium's potency and might cause irreversible problems such as, change in shape of the battery and explosion. Additionally, Cui et al. (2018) stressed out that it is quite possible for Li-ion batteries to burn and create an explosion more than other types of batteries. On top of that, due to the wide temperature range and the challenging conditions that EVs' batteries are subjected to, a BMS is used (Dai et al., 2013; Zheng et al., 2016) to control Li-ion batteries during the charging/discharging procedure (Capasso and Veneri, 2014) and several SoC imbalances during battery's function (Li, 2017). One of BMS's most vital function, as Truchot et al. (2014) supported, is the proper monitoring of battery's SoC, so that battery's pack safety will be ensured (Yang et al., 2018). Therefore, as EVs will be gaining ground in the transportation sector, it is crucial for manufacturers to have an in depth knowledge concerning the optimum charging procedure. Increased lifespan of batteries along with reduced environmental waste depend on it.

At this point, it is worth mentioning that limiting battery's cycle between the suggested range (i.e. 20%–80% of SoC) might seem quite risky, due to the range anxiety phenomenon. Nevertheless, with the existing EVs' distance range (Evrater, 2017), drivers should not feel insecure, at least for their daily routes, which according to Veneri et al. (2012), do not exceed 50 km in 80% of the cases. Range anxiety is a term that refers to the psychological condition of EV users and describes drivers' worry about the remaining EV's power and its sufficiency to reach the chosen destination (Guo et al., 2018; Salah and Kama, 2017).

As mentioned before, this study investigates the energy balance with emphasis on loss reduction of an EV's charging procedure under the scope of the optimum use of EVs' battery. Although there is some published work and researches that deal

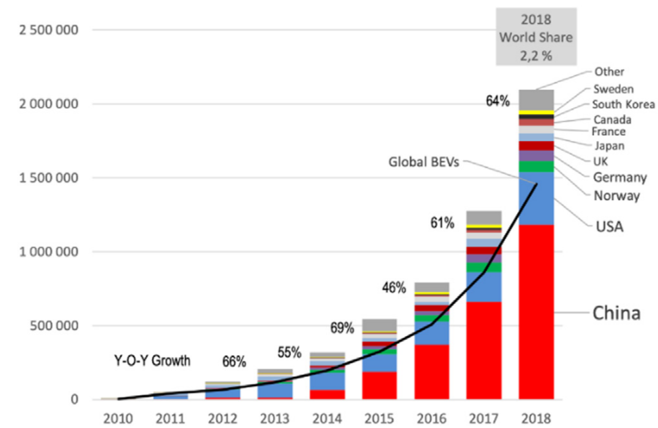

Fig. 1. Global EV sales 2010–2018 (International Energy Agency (I.E.A.) and Organisation for Economic Co-operation and Development (O.E.C.D), 2018; Irle, 0000).

with the energy losses that occur in an EV, few of them focus on the battery's charging procedure and the parameters that cause these losses. Most of them, such as Sinha et al. (2013) deal with the impact of EV charging on the losses in the distribution system while other such as Jajczyk et al. (2017) and Kieldsen et al. (2016) are focused in the EVs' charging stations and propose solutions to reduce losses.

More precisely, US Department of Energy (DOE) (2015, 2017), published a study that depending on the EV's driving cycle, a comparison concerning the energy losses between the electric drive system, the parasitic loads, the wind and rolling resistances, the braking and the battery's charging is made. Chlebis et al. (2014) have made a comparison between fast charging, which according to Li et al. (2020) is causing permanent damage to the battery, and standard charging in order to see if and how energy losses are correlated with the charging current.

Furthermore, Mousavi and Flynn (2016) through different proposed scenarios for the massive EV charging, calculate the energy loss of EVs during the fully charging procedure. On the other hand, a more focused research on electrical losses with measurements that took place inside a laboratory, is that of Apostolaki-Iosifidou et al. (2017). In their case, power losses are quantified in a Vehicle to Grid (V2G) system consisting of two EVs that could both charge their battery and also discharge power back to the grid and their assisting electrical infrastructures; namely, the Electric Vehicle Supply Equipment (EVSE), the breaker panel and the transformer. Furthermore, were taken into account the energy losses between the grid connection point and the EV battery, under different conditions. The study of Spyropoulos et al. (2016), one of the authors of the current work, is separated from others due to the fact that the experiment was based on real-world measurements. According to their work, different patterns adopted during the charging and discharging of the same commercial BEV (but previous model) used in this work. The vehicle discharged and later charged with different charging speeds and climatic conditions, under partial and full load. The significance of the findings and the acquired experience was useful, giving the opportunity to estimate the actual energy consumed and the total efficiency of charging an electric vehicle. Despite the significance of the findings, the research did not take into account the impact that specific charging SoC levels might have on energy losses and the final energy consumption of the tested EV.

The aforementioned studies quantified the electricity losses during EV charging, but none of them took into account the losses above 80% of SoC. More precisely, Mousavi and Flynn (2016) calculated losses until 100% of the charging procedure, while Apostolaki-Iosifidou et al. (2017) conducted their measurements for a SoC range of 20%–80%. The novelty of the current work lies in two crucial facts. Initially, it is based on real-world measurements, contrary to the aforementioned papers and many others that are based on lab simulations. Secondly, it is differentiated from the other studies because it tries to shed light on the SoC area especially between 80%–100%.

2. Methodology

In the literature, several studies have been published that measure EVs' performance concerning energy consumption and electricity losses following specific experimental methodologies in order to obtain realistic and comprehensive results. As Rodrigues Teixeira and Sodré (2016) stated, most of the EV energy measurements are acquired either from laboratory tests or simulations under different driving cycles (e.g. New European Driving Cycle – NEDC, Worldwide Harmonized Light Vehicle Test Procedure – WLTP, World Motorcycle Test Cycle – WMTC etc.). More precisely, several simulation software exist, such as the AVL CRUISE and the AUTONOMIE (Mahmud and Town, 2016). For instance, Varga (2013) utilized the AVL CRUISE model to simulate four different EVs under the NEDC measured energy consumption. Similarly, Mousavi and Flynn (2016) used the DigSILENT Power Factory software in order to calculate EVs' energy losses. Although all different simulation software represent a convenient and low cost approach, they are subject to reliability issues which cannot accurately reproduce real-life conditions.

On the other hand, laboratory tests offer more realistic results compared to simulations. Particularly, Pace and Claessens (2014) tried to measure the energy consumption and charging losses of an EV. Laboratory tests were carried out under the NEDC by using a rolling bench. The rolling bench technique is used to add realistic conditions so that the experiment is close enough to on-road measurements. In the same way, Apostolaki-Iosifidou et al. (2017) utilized sample EV components, in order to measure Grid-Integrated Vehicle System's power losses building circuits and power feed components without driving the car or using any driving cycle simulator. Furthermore, a combination of on-road measurements and rolling bench tests was conducted by Deloof et al. (2003), to obtain energy consumption measurements for five different EVs.

Contrary to all the aforementioned experimental methods, Spyropoulos et al. (2016) utilized an EV under real-world driving conditions and different charging speeds to measure losses during charging. Independent of specific driving cycles or any simulation software, they simply discharged the car by following different routes and different driving styles.

After taking into consideration all the above and since real road conditions are quite difficult to simulate (i.e. weather, wind-road resistance, traffic conditions etc.) the methodology that was followed in this study is based on Spyropoulos et al. (2016) methodology with some improvements. Considering that driving cycles and especially the NEDC, do not reflect real-life driving conditions (Pace and Claessens, 2014; Yuan et al., 2017; Wager et al., 2014), the driving pattern that was adopted in this research represents that of a typical driver. More precisely, a commercial BEV was used which was driven by the research team throughout the experiment. The vehicle was discharged under real-world driving conditions, following a predefined route under an eco-driving behavior until SoC reaches 20%. After the end of its route, the vehicle was charged in the multifunctional autonomous and grid connected, solar EV charging station located at the Soft Energy Applications and Environmental Protection Laboratory (SEALAB) of the University of West Attica (UNIWA). During the charging phase all the necessary measurements were realized by the Laboratory's advanced electronic monitoring system.

Fig. 2. Logic diagram of the experimental process.

At this point it is important to highlight that, due to the fact that the tested BEV does not belong to the SEALAB, but was offered by the BMW dealer company for experimental reasons, almost 1000 km were covered, revealing minor deviation between each measurement. Additionally, the authors' previous experience has shown that 1000 km are sufficient enough for the current project.

2.1. Experiment's realization

In this section, the methodology of the experiment that was followed is described. Fig. 2 below depicts the logic diagram of the experimental process that is divided into three separate phases. Each phase consists of all the required actions that needed to be completed so that the next phase could start. The vehicle was repeatedly discharged by driving it through a predefined route consisting of a variety of traffic conditions and then charging it initially up to 80% of SoC and then up to 100% of SoC. As it will be explained further, a specific methodology protocol was created so that data recording will be as much comprehensive as it could be. The EV was driven only by one person from the authors' team, under a specific driving profile which combined different traffic conditions, so that the experiment will reflect real on-road conditions. Below, in Fig. 2 the three phases of the current research are analyzed.

2.1.1. Phase 1: Pre-discharging inspection

Initially, the vehicle is received from the solar EV charging station located at the SEALAB of UNIWA and is externally checked, mainly for the good condition of the tyres. Once entering the vehicle, the turn-on button is pressed and a second inspection is carried out concerning all the safety and electronic functions of the vehicle. Unless there is any malfunction, all the necessary parameters are reset to zero. These critical parameters, as shown in Fig. 3, include the trip duration (h), the traveled distance (km), the energy consumption (kWh/100 km) and the average speed (km/h). Next, for a more comprehensive data recording a logbook (Fig. 4a) is filled in by the driver before starting the discharge

Fig. 3. Useful information provided by EV's dashboard (Greek version menu).

procedure through driving the vehicle. This logbook contains all the aforementioned parameters accompanied with additional information, which are displayed in the second dashboard of the EV such as the start time and the day of the experimental trip, the initial SoC (%), the remaining distance range (km), the ambient temperature (°C), together with any interesting comment that needed to be noted down during each phase. After all necessary actions took place, the vehicle is ready for the discharging phase.

2.1.2. Phase 2: On-road discharging process

It is worth mentioning that the route selection was decided in order to reflect real traffic conditions. The typical predefined route, which is shown in Fig. 4b, included three main traffic conditions. Namely, a traffic congestion, characterized by increased vehicular queueing, when moving from UNIWA to downtown during rush hour, then a medium traffic condition was followed as the vehicle was driven to the suburbs and finally, since the EV needed to finish its trip at the charging station of the SEALAB it was driven through a highway where low traffic existed. In order to make sure that EV's each route was finished at 20% of SoC, which represents the starting point of the charging procedure, in some cases, where SoC was slightly higher than the 20% (e.g. 23% of SoC), the vehicle was driven within the campus area. In addition to this, an eco-driving profile was followed where no sudden acceleration and braking took place, the air-condition was deactivated throughout the experiment and depending on each traffic condition a steady speed and distance from other vehicles was maintained. It should be noted that, due to the mild Mediterranean climate of Greece – especially during the period that the experiment was conducted – it is untypical for drivers to use air-condition. The vehicle was discharged under real-world driving conditions, following the abovementioned typical route, until SoC indication reaches 20%. Hence, that was the point where the vehicle needed to be at the charging station and represents the end of the second phase.

2.1.3. Phase 3: Charging-data recording process

Before starting the charging procedure the logbook was filled in again with appropriate information acquired during the route (e.g. changes in driving behavior, more or less traffic than the expected one and generally anything that could affect experiment's conditions) and with the final values of the parameters mentioned in Phase 1. Once connected to the charging station, the vehicle's dashboard shows current SoC, the expected time of charging completion and the expected range autonomy (Fig. 5).

2.2. System components

In this section, the whole experimental apparatus is described. The system components consist of three parts: the chosen EV, the Charging Station and the Monitoring System.

Table 1
Technical data of the BEV.

Energy content (rated/usable) in kWh	33.2/27.2
Battery capacity in Ah	94
Rated voltage in V	353
Combined Energy consumption in kWh/100 km[a]	13.1–13.6
WLTP electric range in km	235–255
CO_2 emissions gr/km	0

[a]In accordance with the measurement process as defined by European Regulation (EC) 715/2007.

2.2.1. The chosen EV

The commercial BEV model used is the BMW i3, which is a B-class, high-roof hatchback manufactured and marketed by BMW, with an electric power train using rear wheel drive via a single-speed transmission (Wikipedia, 2018). Moreover, it is packed with a high voltage lithium-ion battery pack (NMC-111). The technical data of the BEV are presented in Table 1, as provided by the official manufacturer's site (BMW Group PressClub, 2016). The i3 is BMW's first mass-produced zero emissions vehicle and has been launched as part of BMW's electric vehicle sub-brand, BMW I (Ewing, 2011).

2.2.2. The charging station

The autonomous/grid connected solar EV charging station (Fig. 6) of the SEALAB of the UNIWA is able to work autonomously using batteries, while it is able to be connected with grid and/or provide V2G facilities. It has also two different charging speeds, i.e. "normal" and "slow". During "normal" charging, high power via a P-charge Wallbox Mono (of up to 22 kW) incorporated in the solar EV charging station is provided. During "slow" charging, the vehicle is connected with a conventional AC 230-volt (16 A) household power socket, incorporated also in the solar EV charging station.

2.2.3. The monitoring system

One of the most important parts in order for measurements to be realized is the electronic monitoring system. It is part of the SEALAB charging station and it contains an integrated web-server unit capable of monitoring data such as, energy (kWh), instantaneous variable data (V, A, W), digital input status etc. The accuracy of the monitoring system depending on the charging current, for the measured kWh, is ±1% (class 1 according to EN62053-21 and class B according to EN50470-1-3). All the monitored data (Fig. 7) are available through a GSM/GPRS modem or Ethernet (direct connected to internet). The data were recorded with a selected step "Δt" representing the mean value of measurements per five minutes.

Fig. 7 presents the EV's charging procedure for two typical days as depicted by the SEALAB's monitoring system. One may see, that the charging procedure was starting at 20% of SoC with the maximum charging power reaching 11 kw. The moment that the EV's SoC level had reached 80% (black vertical line) is also presented. Consequently, after a few minutes, the charging power started to decrease while the charging procedure was reaching to its end (i.e. 100% of SoC). More precisely, at the start of the charging procedure the current is steady at a level, until the voltage will reach a specific level. After that, the voltage is kept constant and the current drops exponentially. That procedure represents the typical Constant Current-Constant Voltage (CC-CV) charge cycle. Furthermore, it should be noted that the drops observed in the figure are the result of SoC and other parameters recording, from EV's dashboard, at regular intervals.

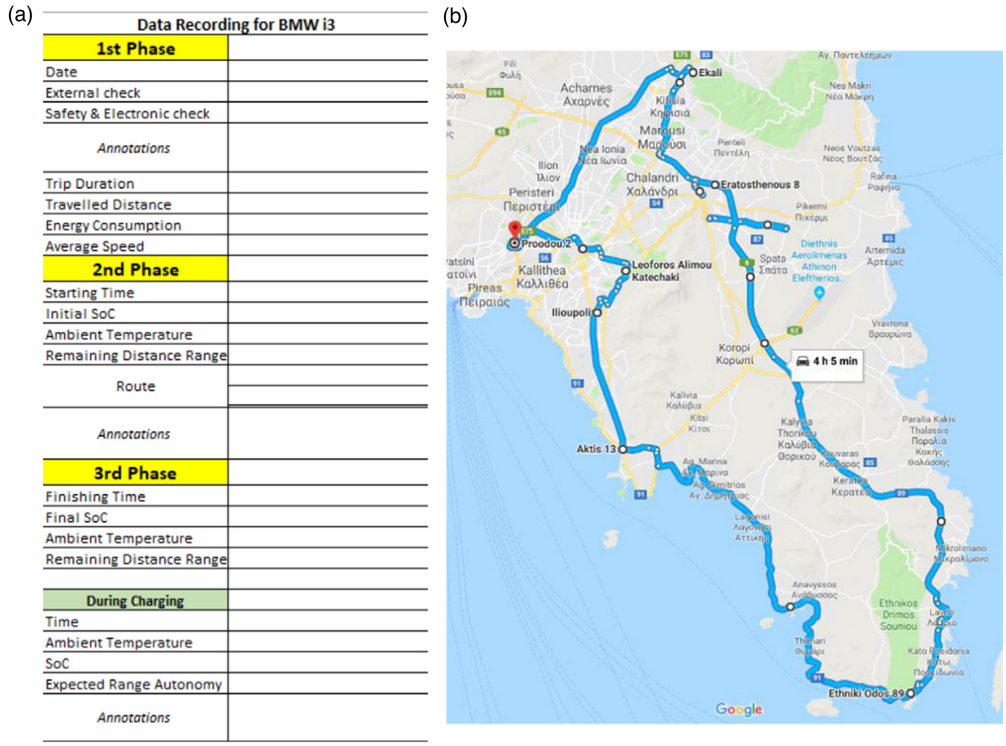

Fig. 4. (a) Experiment's logbook; (b) The typical predefined route.

Fig. 5. EV's dashboard during charging.

Fig. 6. The autonomous/grid connected solar EV charging station of the SEALAB of the UNIWA.

3. Analytical calculations presentation

In order to investigate the difference between the energy consumption "$\overline{C_d}$" (kWh/100 km) that the driver sees on the EV's dashboard and the EV average specific real energy consumption "$\overline{C_r}$" (kWh/100 km), the following equation was used:

$$\overline{C_r} = \frac{\sum_1^N \left(\frac{\sum_1^n P_j \times \frac{\Delta t}{60}}{S_i} \times 100 \right)}{N} \quad (1)$$

where "N" is the number of the routes, "n" is the number of measurements until the selected SoC, "P_j" (kW) is the electrical power from the grid for jth measurement (from 1 to n), "Δt" is the selected step of five minutes and "Si" (km) is the traveled distance for ith route (from 1 to N). Consequently, percentage losses "L" (%), between the average energy consumption that EV's dashboard displays and the average specific real energy consumption, were computed according to Eq. (2):

$$L = \frac{\overline{C_r} - \overline{C_d}}{\overline{C_d}} \times 100 \quad (2)$$

Furthermore, to evaluate if drivers will benefit, from an economic perspective, by limiting the charging procedure between 20%–80% of SoC, rather than fully charging the vehicle (20%–100% of SoC), the cost "$p_{ch}^{k,l}$" (€) for charging an EV is defined as:

$$p_{ch}^{k,1} = \frac{AKT_k \times \overline{C_r^l} \times p_{el}}{100} \quad (3)$$

where "AKT_k" is the average annual kilometers traveled by an urban passenger's car for kth scenario, "$\overline{C_r^l}$" is the average specific real energy consumption for lth selected SoC area and "p_{el}" is the price of electricity (€/kWh). Hence, the fiscal gains "g" (€) from charging between 20%–80% of SoC are defined as:

$$g = p_{ch}^{k,1} - p_{ch}^{k,2} \quad (4)$$

Finally, one may express the driving cost "c_{100}" (€/100 km) using the next equation:

$$c_{100} = \frac{p_{ch}^{k,l} \times 100}{AKT_k} \quad (5)$$

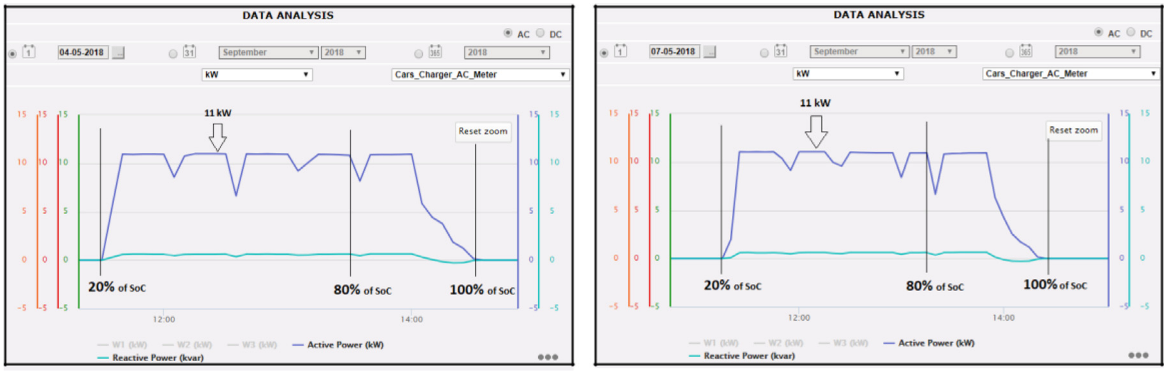

Fig. 7. The Active Power (kW) that the EV was needed during two typical days.

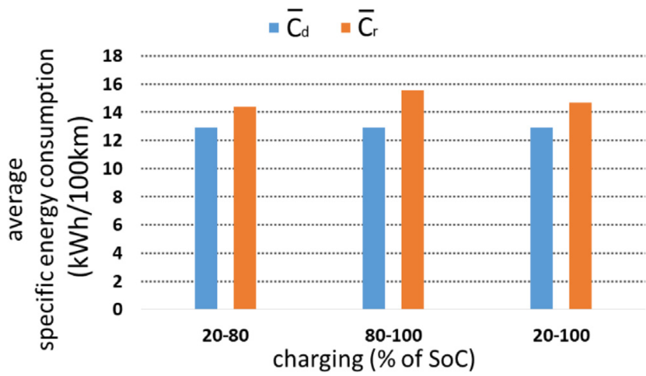

Fig. 8. Average EV's energy consumption as displayed on dashboard compared to the Average specific real energy consumption.

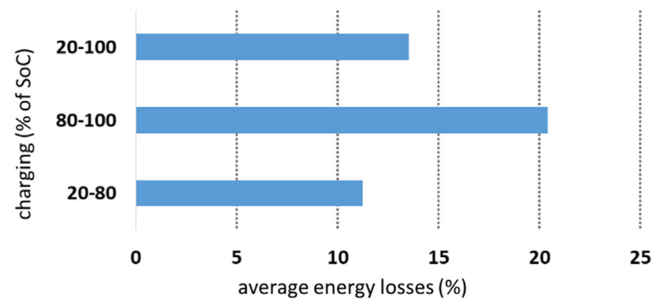

Fig. 9. Average energy losses for the tested SoC areas.

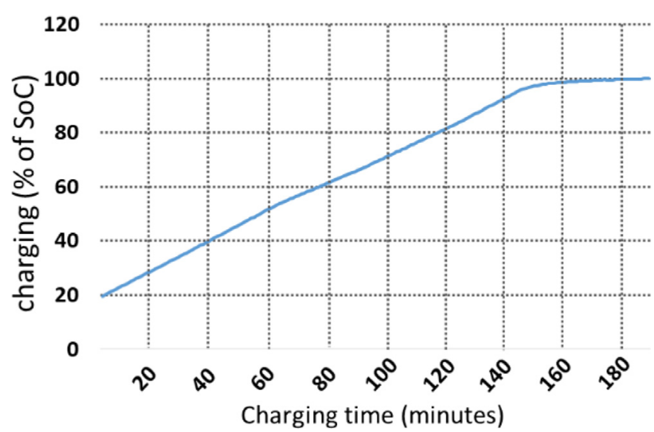

Fig. 10. Average charging time curve.

4. Results and discussion

Fig. 8 presents a comparison between the average energy consumption "$\overline{C_d}$" as displayed on the car's dashboard and the average real energy consumption "$\overline{C_r}$" of the car as measured and calculated by Eq. (1). Particularly, "$\overline{C_r}$" is the energy for which the driver will be charged according to the current price of electricity "p_{el}". Results have shown that for the 20%–100% SoC area, average specific real energy consumption is 1.75 kWh/100 km more than what is displayed on EV's dashboard. Particularly, average specific real energy consumption is 14.67 kWh/100 km, while the average displayed consumption is 12.92 kWh/100 km. When charging procedure exceeds 80% of SoC, that difference reaches 2.63 kWh/100 km.

Furthermore, average energy losses for the tested SoC areas are presented in Fig. 9 which for the 20%–100% SoC area are 13.53%. Moreover, if someone chooses to charge the EV beyond 80% of SoC, losses surpass 20% and are almost double than charging the vehicle between the suggested SoC area. Although, figuring out the reasons for such losses is beyond the scope of this paper, battery losses occur due to a variety of factors. Namely, the electrical power conversion from the AC supply to the DC Li-ion battery for which losses can reach 5% for an AC power of 11 kW (Apostolaki-Iosifidou et al., 2017), wiring losses, several undesired internal electrochemical reactions, an inadequate operation of the BMS and cell warming due to internal resistance (Dai et al., 2013; Lu et al., 2013).

Since time of charging is a very crucial factor, for better understanding EV's battery behavior, a further analysis was conducted to examine the progress of SoC over time. According to Fig. 10 as the EV's, almost empty, battery pack was filling up with the provided energy, SoC levels were linearly increased, at a virtually steady rate, up to a level beyond of which batteries reached 100%. As mentioned before, the charging procedure is based on the CC-CV cycle. That is why in Fig. 10 after a specific SoC level, the charging of the battery slowed down. Note that, the total time to charge the car from 20% to 100% of SoC was, on average, 3 h and 6 min, while for the area between 20%–80% of SoC it took almost 2 h and for the last 20% of SoC the car was charged in virtually one hour.

Another important value is the average autonomy rate, which shows how many kilometers the driver can utilize per hour of charging, depending on the selected charging SoC area. Fig. 11 shows that the suggested, by the research team, SoC area has the highest average autonomy rate among the other two. More precisely, by choosing to operate the EV between 20%–80% of SoC, for every hour of charging almost 71 km are available, contrary to the 80%–100% SoC area where only 44 km per hour of charging are available. Combined with the fact that the needed time for

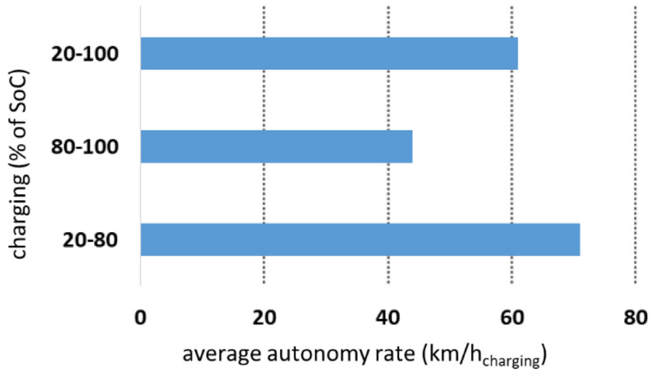

Fig. 11. Average autonomy rate (km per hour of charging).

the 80%–100% SoC area is more than one hour it is not for the driver's benefit to exceed 80% of SoC during charging.

Moreover, it was very important to examine how all the previous results would financially affect an EV user that decided to charge the vehicle in his/her residence. In a nutshell, will the driver save money by limiting the charging procedure between 20%–80% of SoC, rather than fully charging the vehicle? The price of electricity "p_{el}" in Greece, reaches 0.20 €/kWh for an average household (Public Power Corporation S.A. (PPC), 2014; Statista, 2018). Furthermore, three distance scenarios were chosen based on the average annual kilometers traveled (AKT) by an urban passenger's car (Alternative Fuels Data Center (AFDC), 2015; Eurostat, 2015; Federal Highway Administration , FHWA; European Commission, 2015). Since that value was estimated to be 13,000 km/year, it was chosen to represent the middle scenario for the current research. Hence, the other two scenarios were 10,000 km/year and 15,000 km/year respectively.

Table 2 presents the results for each distance scenario. If the driver chooses to follow a full charging strategy, the charging cost will be at 290 €, 378 € and 436 € for an AKT of 10,000 km/year, 13,000 km/year and 15,000 km/year respectively, which represent a very low fuel cost comparing to diesel or gasoline. To check for any fiscal gains "g" a comparison was done between the charging cost for the 20%–100% SoC area and the 20%–80% SoC area. By simply subtracting Eq. (4) the values of each SoC area, depending on the distance scenarios, it can be concluded that there are no significant savings due to low electricity cost by changing the charging procedure of an EV. Finally, the driving cost is on average 3 €/100 km.

Although there is no direct economic benefit, from operating the battery between the suggested SoC area rather than fully charging it, the driver could save money in the long term. By discharging and charging Li-ion batteries below 20% of SoC and beyond 80% of SoC respectively, a decrease in useful cell capacity occurs (Birkl et al., 2017). Therefore, a capacity fade leads to a decreased range, which affects the overall efficiency of the vehicle (Uddin et al., 2016). Since EV's current battery cost ranges between $200 and $250 per kWh and its average capacity is between 40 kWh and 60 kWh, a battery's retail replacement cost varies from $8,000 to $15,000. Additionally, the fact that auto-manufacturers' norm is to provide a battery warranty for eight years or 100,000 miles, there is an imperative need for the optimum use of the battery between the suggested SoC area. Nevertheless, EVs' battery, as all Li-ion batteries, should be periodically calibrated. More precisely, every three months or after 40 partial cycles the driver should let the battery go through a full discharge and then fully charge it up to 100% of SoC (Battery University, 2016a, 2019). This will ensure the proper SoC reporting and therefore that the rated range is correct.

From an environmental perspective, EV's market skyrocketing will inescapable lead to high amount of Li-ion batteries reaching the End of Life (EoL), which in turn will create tons of metal scrap and toxic waste, if ends up in landfills or even mishandled. Particularly as Stringer and Ma (2018) supported, the global stock of EV batteries will reach 3.4 million packs by 2025, compared with virtually 55,000 in 2018. These batteries are not appropriate for EV applications any more, yet they have enough capacity (i.e. 50%–70%) for several stationary functions, such as home, industrial and grid-scale energy storage. After removed from the car, they are normally collected for recycling. But as the Managing Director of Nissan, Francisco Carranza (Gardiner, 2017) claimed, the value of the materials that can be finally redeemed is much lower than that of fully recycling the battery. Since the retired EV batteries have adequate energy for less-demanding tasks (e.g. RES storage) and provided that the application can live for almost 8 to 20 years more (Canals Casals et al., 2017), it is far more valuable to re-use them rather than to recycle them right away. This increasingly popular alternative is known as second-life EV battery market, in which several companies (e.g. Nissan, Hyundai etc.) invest billions. Particularly, Minter (2018) noted, that batteries with re-use potential are priced almost three times more than those more suited for recycling.

Repurposing of EV batteries, has many advantages from an economic and environmental aspect. More precisely, by maximizing retired batteries' value through extending their lifespan in second-life applications could help reduce both the battery cost for EV manufacturers and the purchasing cost for EV customers. As a result, electric passenger cars could become sooner cost competitive with Internal Combustion Engine (ICE) vehicles. Additionally, due to lower re-used batteries' price, the integration of smart grids might be accelerated. From an environmental point of view, the use of repurposed batteries can minimize the footprint of new batteries manufacturing and enhance RES penetration by replacing the non Li-ion storage technology (e.g. lead–acid batteries or any fossil energy source) and thus support a swift to renewable energy. Generally, second-life batteries link the EV and energy storage value chain (Jiao, 2018). Therefore, EV manufacturers should develop a BMS that limits the discharging–charging procedure virtually between 20% and 80% of SoC, in order for the second-life battery industry to utilize healthy and well-used EV accumulators.

5. Conclusions

The main objective of this paper is to quantitatively investigate the battery behavior of EVs during charging procedure. The significance of the findings lies in the fact that measurements were carried out under real-world driving conditions. Namely, after driving the tested vehicle, for almost 1000 km, in a typical predefined route and then plugging it in at the SEALAB's charging station, measurements were taken concerning the vehicle's energy consumption, the energy losses that took place and the kilometers that the driver can utilize per hour of charging. Additionally, specific economic values regarding the charging procedure were defined.

After a thorough literature review concerning the optimum SoC range that Li-ion batteries should operate and the analysis of the abovementioned measurements, noteworthy results were extracted. More precisely, if charging continues beyond 80% of SoC, losses are almost double compared to the suggested SoC area (i.e. 20%–80%) and vehicle's average specific real energy consumption is on average 2 kWh/100 km more compared to what the driver sees on the EV's dashboard. Furthermore, it is for driver's benefit to charge the EV between the suggested SoC area, rather than exceeding 80% of SoC, since more kilometers per hour

Table 2
The annual charging cost for each AKT scenario and the selected level of charging and the corresponding driving cost.

	10,000 (km/year)	13,000 (km/year)	15,000 (km/year)	Driving cost (€/100 km)
Selected level of charging	Charging cost (€)	Charging cost (€)	Charging cost (€)	
20%–80% of SoC	285	370	427	2.85
80%–100% of SoC	308	400	462	3.08
20%–100% of SoC	290	378	436	2.90

of charging are available in a comparatively shorter time. Nevertheless, to ensure that the EV's dashboard will keep correctly reporting the battery's SoC, a periodically fully discharge/charge cycle is needed.

Finally, from an economic and environmental perspective, although the electricity bill will not rise dramatically by charging the car beyond 80% of SoC, the battery's degradation will be accelerated by violating 20% and 80% SoC limits. Hence, the battery will reach its EoL sooner than operating it between the suggested SoC area. This, in turn, will downgrade the battery's value for any second-life application and will increase its environmental footprint. Therefore, a BMS that optionally limits the discharging–charging procedure, through an eco-charging software function on EV's dashboard, virtually between 20% and 80% of SoC, is needed in order EV users to save money in long-terms and electro-mobility market to be enhanced.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Emmanouil D. Kostopoulos: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Validation. **George C. Spyropoulos:** Methodology, Validation, Supervision. **John K. Kaldellis:** Supervision.

References

Alternative Fuels Data Center (AFDC), 2015. Average annual vehicle miles traveled of major vehicle categories. https://afdc.energy.gov/data/ (Accessed 24 October 2018).

Apostolaki-Iosifidou, E., Codani, P., Kempton, W., 2017. Measurement of power loss during electric vehicle charging and discharging. Energy 127, 730–742, https://doi.org/10.1016/j.energy.2017.03.015.

Battery University, 2016a. BU-603:how to calibrate a 'smart' battery. https://batteryuniversity.com/index.php/learn/article/battery_calibration (Accessed 10 December 2018).

Battery University, 2016b. Safety of lithium-ion batteries. https://batteryuniversity.com/ (Accessed 7 April 2018).

Battery University, 2019. How to prolong lithium-based batteries. https://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries (Accessed 3 January 2019).

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L., Mierlo, J.V., 2017. Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. Energies 10 (9), 1314–1334, https://doi.org/10.3390/en10091314.

Birkl, C.R., Roberts, M.R., McTurk, E., Bruce, P.G., Howey, D.A., 2017. Degradation diagnostics for lithium ion cells. J. Power Sources 341, 373–386, https://doi.org/10.1016/j.jpowsour.2016.12.011.

BMW Group PressClub, 2016. Technical specifications for the BMW i3 (94Ah), valid from 07/2016. https://www.press.bmwgroup.com/global (Accessed 11 June 2018).

Canals Casals, L., Amante García, B., Aguesse, F., Iturrondobeitia, A., 2017. Second life of electric vehicle batteries: relation between materials degradation and environmental impact. Int. J. Life Cycle Assess 22 (1), 82–93. http://dx.doi.org/10.1007/s11367-015-0918-3.

Capasso, C., Veneri, O., 2014. Experimental analysis on the performance of lithium based batteries for road full electric and hybrid vehicles. Appl. Energy 136, 921–930, https://doi.org/10.1016/j.apenergy.2014.04.013.

Carrington, D., 2016. Electric cars 'will be cheaper than conventional vehicles by 2022, the guardian. https://www.theguardian.com/environment/2016/feb/25/electric-cars-will-be-cheaper-than-conventional-vehicles-by-2022 (Accessed 22 March 2018).

Chlebis, P., Tvrdon, M., Havel, A., Baresova, K., 2014. Comparison of standard and fast charging methods for electric vehicles. Theoret. Appl. Electr. Eng. 12 (2), 111–116.

Cui, X., Jing, Z., Luo, M., Guo, Y., Qiao, H., 2018. A new method for state of charge estimation of lithium-ion batteries using square root Cubature kalman filter. Energies 11 (1), 209. http://dx.doi.org/10.3390/en11010209.

Dai, H., Zhang, X., Wei, X., Sun, Z., Wang, J., Hu, F., 2013. Cell-BMS validation with a hardware-in- the-loop simulation of lithium-ion battery cells for electric vehicles. Int. J. Electr. Power Energy Syst. 52, 174–184, https://doi.org/10.1016/j.ijepes.2013.03.037.

Deloof, W., Van Mierlo, J., Van den Bossche, P., Jiang, H., Beya, K.B., Maggetto, G., 2003. On-road measuring and testing procedures for electric vehicles, Vrije Universiteit Brussel, Department ETEC, Electrical Engineering & Energy Technology. https://etecmc10.vub.ac.be/publications/evs14wd.pdf.

Drouilhet, S., Johnson, B.L., 1997. A battery life prediction method for hybrid power applications. In: 35th AIAA Aerospace Sciences Meeting and Exhibit. (Reno, Nevada) https://doi.org/10.2514/6.1997-948.

Eider, M., Berl, A., 2018. Dynamic EV battery health recommendations. In: 9th International Conference on Future Energy Systems (ACM E-Energy). (Karlsruhe, Germany). https://doi.org/10.1145/3208903.3213896.

European Commission, 2015. Statistical Pocketbook 2015. https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2015_en (Accessed 24 October 2018).

European Environment Agency (EEA), 2018. Transport greenhouse gas emissions. https://www.eea.europa.eu/airs/2018/resource-efficiency-and-low-carbon-economy/transport-ghg-emissions#tab-based-on-indicators (Accessed 19 April 2019).

Eurostat, 2015. Passenger transport statistics. https://ec.europa.eu/eurostat/statisticsexplained/index.php/Passenger_transport_statistics (Accessed 24 October 2018).

Evrater, 2017. The electric vehicle list.. https://evrater.com/evs#ev-list (Accessed 5 September 2018).

Ewing, J., 2011. Will plug-in BMWs turn enthusiasts on? NYtimes. https://www.nytimes.com/2011/07/31/automobiles/will-plug-in-bmws-turn-enthusiasts-on.html?pagewanted=1&_r=1 (Accessed 23 April 2018).

Federal Highway Administration (FHWA), 2015. Average annual miles per driver by age group. https://www.fhwa.dot.gov/ohim/onh00/bar8.htm (Accessed 24 October 2018).

Fernandez, I., Calvillo, C.F., Sánchez-Miralles, A., Boal, J., 2013. Capacity fade and aging models for electric batteries and optimal charging strategy for electric vehicles. Energy 60 (C), 35–43, https://doi.org/10.1016/j.energy.2013.07.068.

Gardiner, J., 2017. The rise of electric cars could leave us with a big battery waste problem. In: The Guardian. https://www.theguardian.com/international (Accessed 19 December 2018).

Guo, R., Lu, L., Ouyang, M., Feng, X., 2016. Mechanism of the entire overdischarge process and overdischarge-induced internal short circuit in lithium-ion batteries. Sci. Rep. 6, 30248. http://dx.doi.org/10.1038/srep30248.

Guo, F., Yang, J., Lu, J., 2018. The battery charging station location problem: Impact of users' range anxiety and distance convenience. Transp. Res. E 114, 1–18, https://doi.org/10.1016/j.tre.2018.03.014.

International Energy Agency (IEA), 2016. CO2 emissions from fuel combustion by sector in 2014, in CO2 Emissions from Fuel Combustion. In CO2 Highlights 2016 - Excel tables. http://www.iea.org/publications/freepublications/publication/CO2-emissions-from-fuel-combustion-highlights-2016.html (Accessed 6 March 2018).

International Energy Agency (IEA) and Organisation for Economic Co-operation and Development (OECD), 2018. Global EV outlook 2018-towards cross-modal electrification. http://www.oecd.org/publications/global-ev-outlook-2018-9789264302365-en.htm (Accessed 19 April 2018).

Irle, R., 0000. Global EV sales for 2018-Final results, EV-volumes.com, n.d. http://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes (Accessed 15 January 2018).

Jajczyk, J., Dobrzycki, A., Filipiak, M., Kurz, D., 2017. Analysis of power and energy losses in power systems of electric bus battery charging stations. In: International Conference Energy, Environment and Material Systems (EEMS 2017). (Poznan, Poland). https://doi.org/10.1051/e3sconf/20171901027.

Jiang, J., Shi, W., Zheng, J., Zuo, P., Xiao, J.A., Chen, X., Xu, W., Zhang, J.G., 2014. Optimized operating range for large-format lifepo4/graphite batteries. J. Electrochem. Soc. 161 (3), A336–A341. http://dx.doi.org/10.1149/2.052403jes.

Jiao, N., 2018. Second-life electric vehicle batteries 2019-2029 the most comprehensive analysis on the technologies, players, business models and opportunities of second-life electric vehicle batteries, a report provided by idtechex research.

Jiao, N., Evans, S., 2016. Market diffusion of second-life electric vehicle batteries: Barriers and enablers. World Electr. Veh. J. 8 (3), 599–608, https://doi.org/10.3390/wevj8030599.

Kane, M., 2018. Lithium battery pack prices to fall from $209 per kWh now to < $100 By 2025, INSIDEEVs. https://insideevs.com/lithium-battery-pack-prices-to-fall-from-209-per-kwh-now-to-100-by-2025/ (Accessed 22 March 2018).

Kieldsen, A., Thingvad, A., Martinenas, S., Sørensen, T.M., 2016. Efficiency test method for electric vehicle chargers, in international battery. In: Hybrid and Fuel Cell Electric Vehicle Symposium (EVS29). (Montréal, Québec, Canada). http://orbit.dtu.dk/files/137328554/efficiency_paper.pdf.

Li, M., 2017. Li-ion dynamics and state of charge estimation. Renew. Energy 100, 44–52.

Li, Y., K. L.I., Xie, Y., Liu, J., Fu, C., Liu, B., 2020. Optimized charging of lithium-ion battery for electric vehicles: Adaptive multistage constant current–constant voltage charging strategy. Renew. Energy 146, 2688–2699.

Li, J., Murphy, E., Winnick, J., Kohl, P.A., 2001. Studies on the cycle life of commercial lithium ion batteries during rapid charge – discharge cycling. J. Power Sources 102 (1–2), 294–301, https://doi.org/10.1016/S0378-7753(01)00821-7.

Lu, L., Han, X., Li, J., Hua, J., Ouyang, M., 2013. A review on the key issues for lithium-ion battery management in electric vehicles. J. Power Sources 226, 272–288, https://doi.org/10.1016/j.jpowsour.2012.10.060.

Mahmud, K., Town, G.E., 2016. A review of computer tools for modeling electric vehicle energy requirements and their impact on power distribution networks. Appl. Energy 172, 337–359, https://doi.org/10.1016/j.apenergy.2016.03.100.

Marra, F., Yang, G.Y., Træholt, C., Larsen, E., Nygaard Rasmussen, C., You, S., 2012. Demand profile study of battery electric vehicle under different charging options. In: IEEE Power and Energy Society General Meeting. (San Diego, CA, USA) 10.1109/PESGM.2012.6345063.

Minter, A., 2018. China's giving batteries a second life. it's a simple idea. but it may have profound consequences, bloomberg. https://www.bloomberg.com/opinion (Accessed 19 December 2018).

Mishra, S., 2018. Why a BMS is crucial for EV batteries. https://www.electronicsb2b.com/industry-buzz/bms-crucial-ev-batteries/ (Accessed 13 August 2018).

Mousavi, S.M., Flynn, D., 2016. Controlled charging of electric vehicles to minimize energy losses in distribution systems. IFAC-PapersOnLine 49 (27), 324–329, https://doi.org/10.1016/j.ifacol.2016.10.712.

Pace, G., Claessens, L., 2014. Technical report on EV laboratory tests, deliverable 5.1. E-mobility NSR. http://e-mobility-nsr.eu/fileadmin/user_upload/downloads/info-pool/E-MobilityNSR_WP5._R1.pdf (Accessed on 11 June 2018).

Public Power Corporation S.A. (PPC), 2014. https://www.dei.gr/Documents2/TIMOLOGIA/01-01-2018-FINAL/XT-1-1-18-FINAL/Oikiako%20Timologio%20G1%20A4-1-1-18-%CE%95%CE%A4%CE%9C%CE%95%CE%91%CE%A1.pdf (Accessed 18 September 2018).

Rodrigues Teixeira, A.C., Sodré, J.R., 2016. Simulation of the impacts on carbon dioxide emissions from replacement of a conventional Brazilian taxi fleet by electric vehicles. Energy 115 (3), 1617–1622, https://doi.org/10.1016/j.energy.2016.07.095.

Safari, M., 2018. Battery electric vehicles: Looking behind to move forward. Energy Policy 115 (C), 54–65, https://doi.org/10.1016/j.enpol.2017.12.053.

Salah, K., Kama, N., 2017. Inter-service provider charging protocol: a solution to address range anxiety of electric vehicle owners. Energy Procedia 136, 157–162, https://doi.org/10.1016/j.egypro.2017.10.313.

Schoch, J., Gaerttner, J., Schuller, A., Setzer, T., 2018. Enhancing electric vehicle sustainability through battery life optimal charging. Transp. Res. B 112, 1–18, https://doi.org/10.1016/j.trb.2018.03.016.

Sinha, R., Rodríguez Moldes, E., Zaidi, A., Mahat, P., Pillai, J.R., Hansen, P., 2013. An electric vehicle charging management and its impact on losses. In: IEEE PES ISGT Europe. (Lyngby, Denmark) 10.1109/ISGTEurope.2013.6695330.

Spyropoulos, G.C., Petridou, K., St. Liaros, Kaldellis, J.K., 2016. Real World Driving Energy Consumption and Air Pollution Implications of Decarbonizing the Greek Transportation Sector, in: 1st International Conference ENERGY in TRANSPORTATION 2016 (EinT2016), (Athens, Greece).

Statista, 2018. Electricity prices for household consumers in greece from 2010 to 2017, semi- annually (in euro cents per kilowatt-hour). https://www.statista.com/statistics/418083/electricity-prices-for-households-in-greece/ (Accessed 5 November 2018).

Stringer, D., Ma, J., 2018. Where 3 million electric vehicle batteries will go when they retire, Bloomberg. https://www.bloomberg.com/businessweek (Accessed 19 December 2018).

Truchot, C., Dubarry, M., Liaw, B.Y., 2014. State-of-charge estimation and uncertainty for lithium- ion battery strings. Appl. Energy 119, 218–227, https://doi.org/10.1016/j.apenergy.2013.12.046.

Uddin, K., Perera, S., Widanage, W.D., Somerville, L., Marco, J., 2016. Characterising lithium-ion battery degradation through the identification and tracking of electrochemical battery model parameters. Batteries 2 (2), 13, https://doi.org/10.3390/batteries2020013.

US Department of Energy (DOE), 2015. All-electric vehicle: Where does the energy go?. https://www.energy.gov/eere/vehicles/fact-884-august-3-2015-all-electric-vehicle-where-does-energy-go (Accessed 15 June 2018.

US Department of Energy (DOE), 2017. Where the energy goes: electric cars; n.d.. https://www.fueleconomy.gov/feg/atv-ev.shtml (Accessed 15 June 2018).

Varga, B.O., 2013. Electric vehicles primary energy sources and CO2 emissions: Romanian case study. Energy 49, 61–70, https://doi.org/10.1016/j.energy.2012.10.036.

Veneri, O., Ferraro, L., Capasso, C., Iannuzzi, D., 2012. Charging infrastructures for EV: Overview of technologies and issues. In: Electrical Systems for Aircraft, Railway and Ship Propulsion Conference. (Bologna, Italy) http://dx.doi.org/10.1109/ESARS.2012.6387434.

Wager, G., McHenry, M.P., Whale, J., Bräunl, T., 2014. Testing energy efficiency and driving range of electric vehicles in relation to gear selection. Renew. Energy 62, 303–312.

Wikipedia, 2018. BMW i3. https://en.wikipedia.org/wiki/BMW_i3 (Accessed 11 June 2018).

Wu, C., Sun, J., Zhu, C., Ge, Y., Zhao, Y., 2015. Research on overcharge and overdischarge effect on lithium-ion batteries. In: IEEE Vehicle Power and Propulsion Conference (VPPC). (Montreal, Quebec, Canada) 10.1109/VPPC.2015.7353006.

Yang, J., Xia, B., Huang, W., Fu, Y., Mi, C., 2018. Online state-of-health estimation for lithium-ion batteries using constant-voltage charging current analysis. Appl. Energy 212, 1589, https://doi.org/10.1016/j.apenergy.2018.01.010.

Yuan, X., Zhang, C., Hong, G., Huang, X., Li, L., 2017. Method for evaluating the real-world driving energy consumptions of electric vehicles. Energy 141, 1955–1968, https://doi.org/10.1016/j.energy.2017.11.134.

Zheng, L., Zhang, L., Zhu, J., Wang, G., Jiang, J., 2016. Co-estimation of state-of-charge, capacity and resistance for lithium-ion batteries based on a high-fidelity electrochemical model. Appl. Energy 180, 424–434, https://doi.org/10.1016/j.apenergy.2016.08.016.