URBAN LOGISTICS OF SMALL ELECTRIC VEHICLE CHARGED FROM A PHOTOVOLTAIC CARPORT

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Summary

The technology of photovoltaic solar cells can be combined with the technology of electric vehicles. During charging electric vehicles with Renewable Energy Sources (RES) as well as during their use to the atmosphere are not emitted any pollutions. The article presents a carport designed for charging electric vehicle. Paper analyzed the power course generated by the photovoltaic system in different weather conditions. As a result of the comparison with the current demands of the electric vehicle battery during the charging process the optimal way of battery charging process was discussed. Later in the article presents logistics research on charging battery of an urban vehicle used frequently by catering companies to distribute products. The authors' aim was to determine the actual range of the small electric vehicle on a single charge, as well as to statistically compile driving parameters in conditions of urban traffic in Lublin. The process of using such a vehicle has been analyzed, including the necessary battery charging. On the basis of the tests results a set of recommendations for small electric cars users was made in order to help increase the range of the vehicles in traffic and lengthen battery life.

Keywords: electric vehicle, city logistic, battery charging

1. Introduction

Electric vehicles, which stand out in terms of design, are increasingly becoming an indispensable part of the urban landscape [9]. On the one hand, there is a stationary element in the form of electrical vehicle's battery charging process at public charging points. These processes are subject to logistical planning aimed to optimize vehicle charging and properly utilize available charging infrastructure. On the other hand, there is a dynamic element – driving such a vehicle. A major logistic challenge in this case is to plan long, national or international routes due to the limited autonomy of electric vehicles resulting from the limiter range as well as from a small number of battery charging stations.

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The steep drop in traction batteries price caused by rapid development of new materials and manufacturing technologies has enabled the considerable expansion of electric vehicles on the markets in Western Europe, the USA and Asia in recent years [22]. Self-evident constructional advantages and low electricity costs (if it is energy from RES) ever more often determine the choice of an electric vehicle in urban logistics.

Proper exploitation of electric vehicles' assets will create competitive advantages over vehicles with internal combustion engines [5]. An electric car can not only constitute pro-ecological image of a company, but also be a source of economic savings [7].

Changing a vehicle with an internal combustion engine to an electric vehicle is associated with a change in habits related to the use and maintenance of the vehicle [12]. The indirect link that helps in such a transition is undoubtedly hybrid vehicles. Their owners could get acquainted with some of the advantages of an electric drive, such as driving in urban conditions using only an electric drive. They also got acquainted with duties related to the need to recharge traction batteries (in the case of plug-in hybrids).

Electric vehicles have many advantages over vehicles powered by combustion engines. Their main advantages when it comes to use is lack of gearbox. The performance offered by the latest PMSM and BLDC electric motors allow you to get rid of the gearbox. Sometimes one reducer is used. High acceleration, resulting from the characteristics of the drive torque course, combined with a low center of gravity allow each user to feel like a sports car driver.

However, the most important advantage of electric cars is their zero emission in the place of use. Despite the introduction of increasingly restrictive emission standards (Euro 6), vehicles with internal combustion engines contribute significantly to air pollution in the centers of big cities [8]. Current European and global trends include the largest possible use of vehicles with eco-friendly electric drive. In many countries government subsidies can be obtained to purchase an electric vehicle. Increasingly, public transport fleets are based on electric vehicles.

To enjoy the use of an electric vehicle, we must first charge its traction batteries. For this you need the necessary infrastructure including: a parking place, a charging pole or an external charger with certain parameters, electrical wiring with appropriate plugs and a system for accounting for the electricity used. Issues related to the availability of electric vehicle charging infrastructure and its effective use could be the subject of logistic planning [19].

2. Development of electric vehicles' charging infrastructure

Increasing every year number of electric vehicles requires increasing amount of charging stations. The volume of the market can be demonstrated by the number of cars sold on particular markets. In the United States in America, almost 200,000 electric [EV] and hybrid vehicles with the possibility of external charging (PHEV) were sold [22] in 2017. According to the Alternative Fuels Market Observatory report, in 2017, 216 566 EVs were sold in the European Union. In Poland, out of car showrooms in 2017, exactly 1,068 EVs left [23].

An increasing number of electric vehicles on the European and Polish market requires adequate infrastructure to charge them. We are talking here not only about the appropriate number of chargers of particular types [2] but also about their proper location in city centers and near large communication routes [3].

At the moment, both scientists and engineers from industry are working on methods of fast charging of traction batteries. They meet many challenges in this area. Belong to them:

- Limitations related to charging with high currents of the most popular lithium-ion batteries type NMC [11]. The answer is to be new LTO batteries capable of taking charging currents much higher [17, 18]. The testing ground for this type of research are electric buses with battery packages with a capacity of often more than 200 kWh [20]. For such applications, on-board battery recharging (AC) systems, quick external chargers (DC) and maintenance-free recharging with a pantograph (DC) are continually developed [14].
- The need to cool high-voltage DC cables as well as the traction batteries themselves. Some car manufacturers have long decided on liquid cooling battery packs (BMW, Ford), while others have not used such solutions (Tesla, Nissan) so far. The cooling and heating of battery packs contributes evidently to the conditioning of the thermal state of the battery during charging [4] and makes it easier to start working in winter conditions by allowing a higher current load of the battery [10].
- The need to develop external DC chargers with higher power. Currently, the most popular chargers in Europe are 40 or 50 kW. For example, Tesla vehicles, equipped with 100 kWh battery packs, would have to be fully charged for more than 2 hours (for a 50 kW charger) or 3 (for a 40 kW). Following the example of an American competitor, European companies are also increasingly offering 100 kW chargers. Advanced development works on 150 and 350 kW DC chargers are also ongoing [24]. The latter must have liquid-cooled charging sockets as well as high-voltage cables.
- Lack of power network infrastructure ensuring power consumption of 100 kW and higher [6]. In our country, we can only afford to mount chargers up to 50 kW. A few Tesla Supercharger put into use testify to the fact that we can overcome such barriers. There is also a question: Where should the energy for charging electric vehicles come from? [13].

However, a well prepared electrification strategy, e.g. for a given European city, can posit building of necessary infrastructure first, in order to encourage the purchase of electric cars. Charging stations should be accessible when a vehicle in parked for several hours, namely in a home garage and at work. The problem arises when a person does not own a garage or works in the centre of a crowded city. The only solution in those cases is to create a public infrastructure for charging electric vehicles. Its terms of use and range (the number of parking places and the amount of different types of plugs) should be constantly monitored as well as expanded according to the current needs and foreseeable trends.

The offer presented by manufacturers of electric vehicles charging stations stems from customers' real needs and consists of:

a) wall mounted garage charging points,

b) parking poles in dedicated areas in city centers,

c) parking poles in shopping centers (figure 1),

d) parking poles near popular restaurants and cafés,
e) parking poles at gas stations (usually on motorways),
f) parking poles connected to photovoltaic cells – current development trend.

Fig 1. A parking post in one of shopping centers in Lublin

Due to the developnemt of high-speed electric vehicle charging technology, stations capable of charging batteries to SOC=80% in less than half an hour appear more and more often also in Poland.

3. Photovoltaic carport description

Combining technology applied in electric vehicles with the possibility to charge them using Renewable Energy Resources is the most environmentally-friendly solution for powering vehicles [1]. To charge electric vehicles a photovoltaic carport with a peak power of 3 kWp was used [7]. Previous research has shown that an on-grid system is essential when connecting a carport to an electrical grid. It enables complete utilization of the electric power generated to charge a vehicle by returning possible excess back to the grid.

Photovoltaic carport consists of 12 monocrystalline photovoltaic panels made in glass-glass technology, each with an individual optimizer. The carport is shown in figure 2.

Fig. 2. Photovoltaic carport used to charge electric vehicles

12 photovoltaic panels with individual optimizers are connected to a single-phase inverter. The inverter efficiently converts direct current from solar panels into alternating current which can be fed to the electric grid. Every photovoltaic panel is identified and activated individually by the inverter. Power optimizers are direct current DC-to-DC converters connected to PV modules in order maximize energy extraction by autonomously tracking maximum power point (MPPT) at the module level. Power optimizers also regulate the voltage of the modules array and keep it at stable level, regardless of the array's length or environmental conditions.

The inverter is also responsible for monitoring each panel and sending measurement data to the central server. Monitoring portal is connected to the Internet. User-friendly software allows a temporary preview of photovoltaic system parameters, as well as current and forecasted weather conditions. The portal automatically generates daily, weekly, monthly and yearly reports presented as clear visualizations (figure 3) or charts (figures 4 and 5).

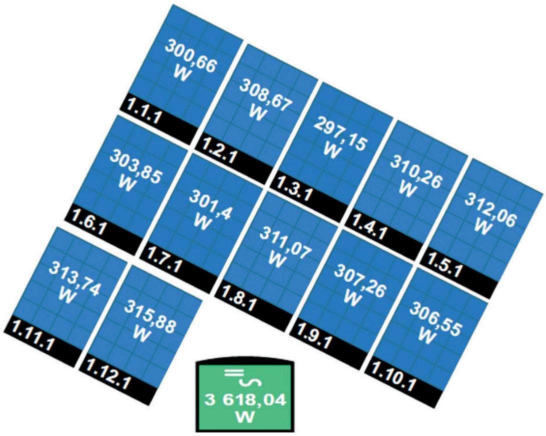

Fig. 3. Monitoring of individual photovoltaic panels

Figure 4 presents the process of generating power by the photovoltaic system in one week in June 2017. During this period Carport produced and fed into the grid 124.95 kWh of energy. The daily amount of electric energy generated in June 2017 is shown in figure 5. During this period Carport produced and fed into the grid 486.88 kWh of energy.

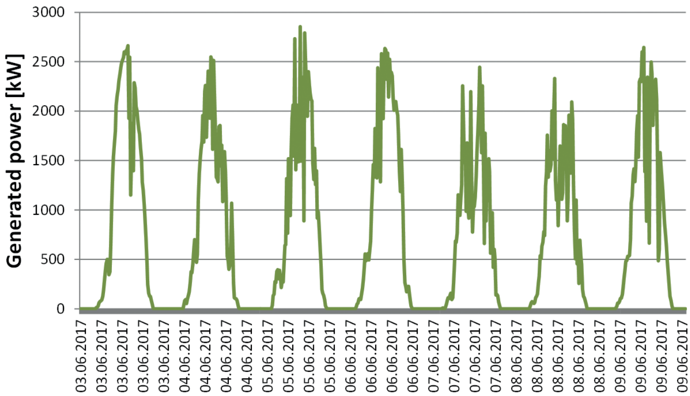

Fig. 4. The process of generating power by the photovoltaic system in one week

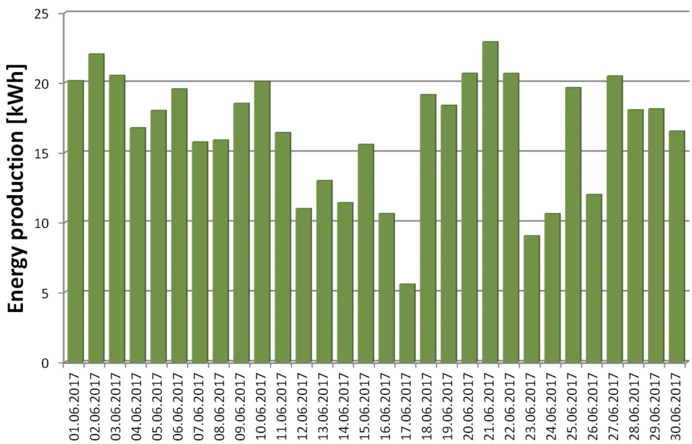

Fig. 5. The amount of energy generated by the photovoltaic system in one month

Since the launch in 04.05.2016 Carport has produced and fed into the electrical grid 4.54 MWh of energy (as of 19.09.2017).

4. Testing the process of charging electric vehicles from photovlotaic carport

Photovoltaic carport was built for the sole purpose of using Renewable Energy Resources to charge a small, urban vehicle with electric drive (figure 6). Carport is located next to the building of Lublin Science and Technology Park and can be accessed by guest vehicles adapted to charging from the 230 V grid (figure 7).

Fig. 6. An electric car during charging

Fig. 7. An electric car during charging from carport

The demand for electric power during the charging process of a small urban electric car has been determined by measuring basic electrical parameters during a standard charging from a full discharge to a full charge of a battery. The instantaneous power needed to charge in the beginning of the process amounted to 1.7 kW and increased to ca. 2kW at the end of the charging process (figure 8). The entire process required ca. 6.1 kWh of energy and lasted ca. 3.5 hours (figure 9).

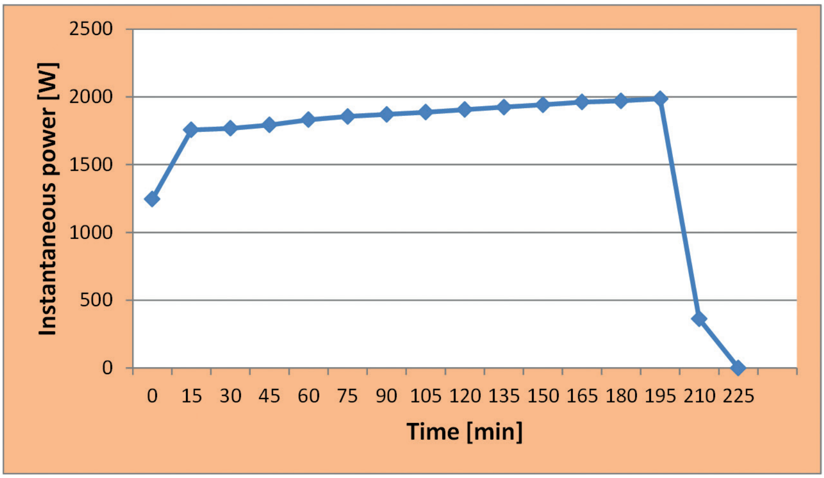

Fig. 8. The demand for electric power during charging an electric vehicle

As it can be seen in the chart presented in the figure 10, during the charging process of a small urban car there is a 200 minute period characterized by a proportional relation between battery's state of charge and the energy consumed on charging. In this period the battery's state of charge reaches 90%. Remaining 10% is replenished over the last minutes of charging. The car's instruction manual states that the charging process of a traction battery can be started or stopped at any given moment, which makes even a brief charging a viable option.

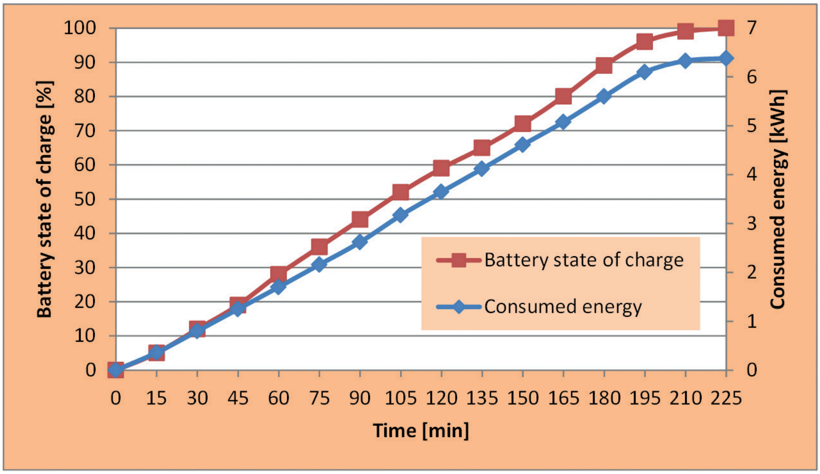

Fig. 9. The chart of the battery charging process, including energy consumption

As a result of the research important information has been obtained, on the basis of which logistic assumptions regarding the charging process can be made. It can be assumed that the relation between the state of charge (SOC in %) and the charging time is linear. The battery can be fully charged in 3.5 hours, consuming 6 kWh of electrical energy. These assumption will be used in planning routes and daily range of the vehicle.

5. Logistic planning of the electric vehicles routes and processes of charging from photovoltaic carport

Small urban vehicle range tests were done after a single battery charging. The tests were carried out in order to inspect the condition of the battery after 3 years of use, which translates into 18,000 km driven. Figure 10 shows the actual vehicle range depending on the average driving speed for two values of the average driving speed. There is an apparent relation between average speed of a car and its range. In Lublin center traffic (average speed 30 km/h, not exceeding 50 km/h) the vehicle was able to travel nearly 80 km on one full battery charge. When the average speed was increased to 75 km/h on the Lublin beltway, the range of the vehicle decreased significantly to slightly above 50 km. Similar tests were done multiple times. Moreover, the tests proved there was no noticeable decrease in the traction battery capacity after nearly 3 years of use, driving over 18,000 km and completing ca. 600 charge cycles. The results will be used as basis in discussing two cases of electric vehicles' utilization in urban logistics.

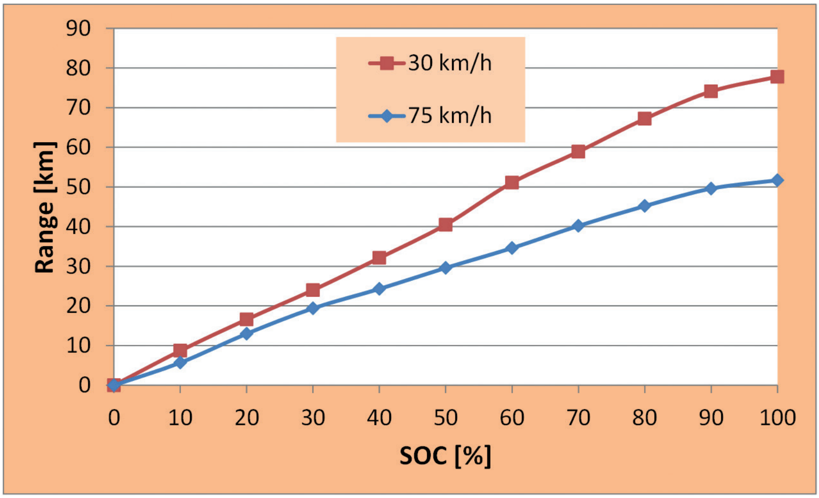

Fig. 10. The range of the small urban vehicle depending on the average driving speed

Thus, the following assumptions regarding the use of a small urban vehicle with electric drive can be made. In case 1 (presented in the table 1) we consider the use of the vehicle with the average speed V_{30} (30 km/h). We start with batteries fully charged (SOC = 100%). During an 8-hours working day it is possible to travel around 160 km (Phase 1+2+3). During a 16-hours working day it is possible to travel 240 km (Phase 1+2+3+4+5). Day ends with an overnight charging from an electrical grid (Phase 6). Depending on the season of the year it will not always be possible to carry out the charging (Phase 4) from photovoltaic carport. Winter days will be too short for charging with solar energy.

Table 1. Daily vehicle utilization for the average speed V30

Charging approach	**Range for V_{30} [km]/ time [h]**	**Charging from carport [h] to SOC 100%**	**Range for V_{30} [km]/ time [h]**	**Charging from carport [h] to SOC 100%**	**Range for V_{30} [km]/ time [h]**	**Overnight charging from the grid to SOC 100%**
Without charging the battery	80 km/ 2,66 h	3,5 h	80 km/ 2,66 h	3,5 h	80 km/ 2,66 h	3,5 h
Phase	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6

In case 2 (presented in the table 2) we consider the use of the vehicle with the average speed V_{75} (75 km/h). We start with batteries fully charged (SOC = 100%). Driving with the average speed V_{75} during an 8-hours working day it is possible to travel 100 km (Phase 1+2+3) and almost fully recharge the battery (Phase 4). During a 16-hours working day it is possible to travel 200 km (Phase 1+2+3+4+5+6+7). Day ends with an overnight charging from an electrical grid (Phase 8)

Table 2. Daily vehicle utilization for the average speed V75

Charging approach	Range for V_{75} [km]/time [h]	Charging from carport [h] to SOC 100%	Range for V_{75} [km]/time [h]	Charging from carport [h] to SOC 100%	Range for V_{75} [km]/time [h]	Overnight charging from the grid to SOC 100%	Range for V_{75} [km]/time [h]	Overnight charging from the grid to SOC 100%
Without charging the battery	50 km/ 0,66 h	3,5 h	50 km/ 0,66 h	3,5 h	50 km/ 0,66 h	3,5 h	50 km/ 0,66 h	3,5 h
Phase	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8

When it comes to traction battery charging, both cases (1 and 2) assume an adverse scenario for the batteries themselves as well as for the company using the vehicle. For current lithium-ion batteries full discharge is not recommended, because it can significantly shorten battery life. Electric vehicles manufacturers advise instead to recharge batteries as frequently as possible. Furthermore, without frequent recharging the vehicle is rendered unusable during the entire period of full charging. Depending on the industry and the specific nature of a business this approach can be either possible or impossible to implement properly. For catering companies it is rather unacceptable. In such cases a company should be in possession of several electric vehicles or batteries packs for quick replacement. When some of them are used, others could be recharged. Fast developing technologies of accelerated and high-speed charging can facilitate the process to a great extent. However, they require additional electric power supply infrastructure. The latest models of passenger car chargers feature power consumption of over 100kW. Not every country (including Poland) are prepared to accept such chargers.

An alternative approach, recommended by the author, is to recharge a battery in every spare moment, regardless of the initial SOC and the length of the charging process. Such approach will not affect the projected daily range.

6. Conclusion

The article presents logistics research on charging battery of an urban vehicle used frequently by catering companies to distribute products. The vehicle is available in two models – a two-seater or a single-seater with cargo space. The authors' aim was to determine the actual range of the car on a single charge, as well as to statistically compile driving parameters in conditions of urban traffic in Lublin. The process of using such a vehicle has been analyzed, including the necessary battery charging. On the basis of the tests results a set of recommendations for electric cars users was made in order to help increase the range of the vehicles in traffic and lengthen battery life.

The research has shown that during an 8-hour working day it is possible to travel 100 to 160 km, depending on the average driving speed. During a 16-hour working day it is possible to drive 200 to 240 km, also depending on the average driving speed. The increase in average driving speed significantly reduces the vehicle's range.

In addition to the detailed conclusions, the authors also formulated general conclusions:

1. Small electric vehicles can be powered by Renewable Energy Resources.
2. The autonomy of existing electric vehicles is not sufficient to compete with vehicles with internal combustion engines.
3. The infrastructure for electric vehicles charging in Poland is insufficient.
4. Electric urban vehicles provide better dynamics and driving comfort than vehicles with internal combustion engines.
5. Full charging as well as recharging of the electric vehicle battery from the photovoltaic panels reduces the CO_2 emission to the atmosphere.

References

[1] Aguado-Monsonet M., The enviromental impact of photovoltaic technology, EC Technical Report Series 1998.

[2] Capasso C., Veneri O.: Experimental study of a DC charging station for full electric and plug in hybrid vehicles, Applied Energy, Volume 152, 15 August 2015: 131-142.

[3] Chung B., Park S., Kwon Ch.: Equitable distribution of recharging stations for electric vehicles, Socio-Economic Planning Sciences, Volume 63, September 2018: 1-11.

[4] Hall F., Touzri J., Wußler S.: Experimental investigation of the thermal and cycling behavior of a lithium titanate-based lithium-ion pouch cell, Journal of Energy Storage, Volume 17, 2018: 109-117.

[5] Informator techniczny BOSCH, Napędy hybrydowe, ogniwa paliwowe i paliwa alternatywne, Wydawnictwo Komunikacji i Łączności, wydanie 1, Warszawa 2010.

[6] Levinson R. S., West T. H.: Impact of public electric vehicle charging infrastructure, Transportation Research Part D: Transport and Environment, Volume 64, October 2018: 158-177.

[7] Małek A., Kowalczyk D., Analiza procesu ładowania pojazdu elektrycznego z fotowoltaicznych ogniw słonecznych. AUTOBUSY – Technika, Eksploatacja, Systemy Transportowe 6/2016.

[8] Merkisz J., Pielecha J., Radzymirski S., Emisja zanieczyszczeń motoryzacyjnych w świetle nowych przepisów Unii Europejskiej, Wydawnictwo Komunikacji i Łączności, 2012.

[9] Merkisz J., Pojazdy hybrydowe i elektryczne, a sprawa Polska. Instytut Transportu Samochodowego, Warszawa 2012.

[10] Motoaki Y., Yi W., Salisbury S.: Empirical analysis of electric vehicle fast charging under cold temperatures, Energy Policy, Volume 122, November 2018: 162-168.

[11] Nitta N., Wu F., Lee J. T.: Li-ion battery materials: present and future, Materials Today, Volume 18, Issue 5, 2015: 252-264.

[12] Philipsen R., Brell T., Brost W.: Running on empty – Users' charging behavior of electric vehicles versus traditional refuelling, Transportation Research Part F: Traffic Psychology and Behaviour, Volume 59, Part A, November 2018: 475-492.

[13] Raugei M., Hutchinson A., Morrey D.: Can electric vehicles significantly reduce our dependence on non-renewable energy? Scenarios of compact vehicles in the UK as a case in point, Journal of Cleaner Production, Volume 201, 10 November 2018: 1043-1051.

[14] Rogge M., Wollny S., Sauer D. U., Fast Charging Battery Buses for the Electrification of Urban Public Transport – A Feasibility Study Focusing on Charging Infrastructure and Energy Storage Requirements, „Energies" 2015, No. 8.

[15] Rudnicki T., Pojazdy z silnikami elektrycznymi. Zeszyty Problemowe – Maszyny Elektryczne Nr 80/2008.

[16] Technology Roadmap Electric and plug-in hybrid electric vehicles, Paris, OECD/IEA, 2011.

[17] Wang L., Wang Z., Ju Q.: Characteristic Analysis of Lithium Titanate Battery, Energy Procedia, Volume 105, May 2017, Pages 4444-4449.

[18] Wang Y., Chu Z., Feng X.: Overcharge durability of Li4Ti5012 based lithium-ion batteries at low temperature, Journal of Energy Storage, Volume 19, October 2018: 302-310.

[19] Wang Y-W., Lin C-C., Lee T-J.: Electric vehicle tour planning, Transportation Research Part D: Transport and Environment, Volume 63, August 2018: 121-136.

[20] Yilmaz M., Krein P. T., Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles, „IEEE Transactions on Power Electronics" 2013, Vol. 28, No. 5.

[21] https://monitoring.solaredge.com – access date 19.09.2017 r.

[22] http://samochodyelektryczne.org/wyniki_sprzedazy_ev_phev_w_kalifornii_w_2017r.htm – access date 23.03.2018.

[23] http://www.orpa.pl/sprzedaz-pojazdow-elektrycznych-w-polsce-europie-podsumowanie-2017-r-2/ – access date 23.03.2018.

[24] https://elektrowoz.pl/ladowarki/mega-e-uruchamia-pierwsza-stacje-ladowania-350-kw-bedzie-tez-w-polsce/ – access date 23.03.2018.