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Performance analysis of a lithium-ion battery of an electric vehicle under various driving conditions

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Abstract Conventional fuels are the primary source of pollution. Switching towards clean energy becomes increasingly necessary for sustainable development. Electric vehicles are the most suitable alternative for the future of the automobile industry. The battery, being the power source, is the critical element of electric vehicles. However, its charging and discharging rates have always been a question. The discharge rate depends upon various factors such as vehicle load, temperature gradient, surface inclination, terrain, tyre pressure, and vehicle speed. In this work, a 20 Ah, 13S-8P configured lithium-ion battery, developed specifically for a supermileage custom vehicle, is used for experimentation. The abovementioned factors have been analyzed to check the vehicle's overall performance in different operating conditions, and their effects have been investigated against the battery's discharge rate. It has been observed that the discharge rate remains unaffected by the considered temperature difference. However, overheating the battery results in thermal runaway, damaging and reducing its life. Increasing the number of brakes to 15, the impact on the discharge rate is marginal; however, if the

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number of brakes increases beyond 21, a doubling trend in voltage drops was observed. Thus, a smoother drive at a slow-varying velocity is preferred. Experiments for different load conditions and varying terrains show a rise in discharge with increasing load, low discharge for concrete, and the largest discharge for rocky terrain.

Keywords: Clean energy; Lithium-ion battery; Discharge rate; Voltage; EV; Supermileage; Environment

1 Introduction

Encouraging renewable and alternative energy is the need of time for sustainable development. With the current speed of globalisation and thriving industrialization, the worldwide energy demand has increased promptly. Indeed, fossil fuels have made a significant impact in the previous two centuries in worldwide development; however, global climate change and the depletion of fossil fuels have become major constraints. As per the data mentioned in the literature [1–3], it has been anticipated that with the 5% annual increment in the present production rate of oil (1.41%), coal (1.64%), and natural gas (2.69%), the fossil fuels will barely survive for next 50 years. Moreover, annual fossil fuel consumption on a global scale has increased by 1.77%. However, the spread of coronavirus disease 2019 (COVID-19) and subsequent restrictions have impacted such fuels' international supply and demand. Restricting the use of fossil fuels is one of the prime focuses of the Paris Climate Accords adopted in 2015; the committee has agreed to decrease the overall temperature below 1.5°C [3, 4].

Alternative energy sources have been promoted and commercialized to overcome environmental and other major challenges [5]. As per the latest data in the literature [6, 7], about 22 cities out of 30 most polluted cities in the world are from India. Air pollution has become a major global issue, and millions of lives are at risk due to severe air pollutants released from the transportation and industrial sectors [8, 9]. After so many cautions and various action plans, the issue is still showing an alarming trend. One such modification and action is switching towards electric or hybrid vehicles. Although there are lots of constraints, the popularity of electric vehicles is increasing. Consequently, lots of research is being processed to overcome the shortcomings and improve overall performance. Furthermore, the need for electric vehicles are even more justified, considering the environmental degradation. The search for alternative power sources has been a constant struggle, and electric cars can potentially be a solution. The overall cost of ownership, including battery cost, drivetrain cost, fuel prices, and maintenance costs with time, will have better pricing in the future with more research in the fields of battery technology [10].

Electric mobility is an important aspect of the energy transition. Electric vehicles (EVs), even with lower maintenance, higher well-to-wheel efficiency, and the obvious environmental and economic benefits, still have the biggest challenge of low range, low efficiency, longer charging times, limited infrastructure, and high capital cost of batteries [11, 12]. For an electric vehicle to be resourceful, the main characteristics to be focused on are that it should run entirely on cheap, small, and efficient electric motors, requires low maintenance, has a large battery for long range, and has a fast-charging capability. Consequently, battery charging conditions should be maintained to supply uninterrupted power [13]. Therefore, significant research, analysis, and optimization of batteries, which act as a portable energy reserve for an e-vehicle, are of utmost importance. The longevity of batteries is related to charging and discharging as well as ambient conditions of use.

Among many other batteries, the lithium-ion rechargeable battery has been a focal point of research and application. It has the potential to power not only electric vehicles but also various electronic consumer goods, energy storage systems, aerospace, robotic and military applications [14, 15]. Compared to traditional batteries, lithium-ion batteries charge faster, last longer, and have high power density for longer battery life in a lighter package [16, 17].

Lithium atoms at the anode get ionized and separated from their electrons during the lithium-ion battery's discharge cycle. The lithium ions then move to the cathode, recombining with electrons and getting electrically neutralized. They move through the electrolyte and are small enough to pass through a micro-permeable separator between the anode and the cathode [18]. Due to the small size of lithium-ion, lithium-ion batteries can produce a very high voltage and charge storage per unit mass and volume.

- Lithium (Li) batteries are powered by the lithium oxidation reaction:

$$\mathrm{Li} \rightarrow \mathrm{Li}^{+} + e^{-} \ (3.05\ \mathrm{V}).$$

- The oxidation potential pushes electrons generated at the anode through external circuitry, thus delivering energy.

- Different types of materials can be used as electrodes in a lithium-ion battery. One of the most typical compositions is that of lithium cobalt oxide (cathode) and graphite (anode), which can be usually discovered in compact electronic devices such as mobile phones and laptops [19]. Additional materials that can be used as cathodes include lithium manganese oxide and lithium iron phosphate. Lithium-ion batteries ordinarily use ether as an electrolyte.

1.1 Advantages

Lithium-ion cells offer a considerable advantage of low self-discharge rate compared to rechargeable cells, namely, NiMH and Ni-Cad forms. This helps deal with the concern of the range of EVs and more prolonged operations before discharge. The cell voltage of lithium-ion battery cells is higher than other standard batteries available; thus, the number of cells required for the same power generation is smaller. Lithium is the lightest of all metals, has the greatest electrochemical potential, and provides the largest energy density for its weight [20]. Two of the main reasons electric cars failed in the past were the size and weight requirements of the battery installed. Earlier, fuel-powered vehicles proved to be a more convenient and effective way of energy storage [21]. However, the development in battery technologies has made them wonderfully compact and light. With such progress, electric cars will be lighter than ever, taking the weight of the drivetrain and the energy storage together into account. Lithium-ion batteries have a reasonably high energy and power density. The broadly accepted lithium-ion battery should have a longer life along with high energy intensity [22, 23].

1.2 Disadvantages

One charge plus one discharge is known as a cycle, and the number of times a battery supports its charging and discharging without its decay is called the life cycle. The battery life of lithium-ion batteries isn't just dependent on life cycles but also on environmental conditions. Exposing them to high temperatures reduces their capacity. Also, lithium is an abundantly available resource, but its current extraction is not cost-effective [24].

The current energy densities of batteries aren't at par with the fuels used in IC engines. Battery charging infrastructure is currently under development as well. Controlled charging is an additional requirement for the safe operation of the battery and the vehicle. To ensure continuous safe use of the battery without its degradation, a novel technique, i.e., a dynamic early recognition framework was proposed to distinguish the abnormal batteries from normally degrading batteries before their capacity drops [25].

Electric vehicles may catch fire as the Lithium-Ion battery is susceptible to a short circuit within one or more cells that make up the battery [26]. The overheating batteries could result in thermal runaway, damaging the vehicle and its life [27]. The heat can ignite the chemicals within the battery, and the fire can spread rapidly and efficiently. Various articles in the literature have discussed the way to safeguard the battery and hence the electric vehicle. Consequently, a control strategy was discussed by Dar *et al.* [28] to protect the battery and enhance its life. The article proposed an offboard charger for charging lithium-ion batteries used in EVs. The methodology used for charging safeguards the battery by protecting the battery from overvoltages. The considered charger has the ability to transfer power in two directions to transfer the additional power back to the grid and hence, protect the battery from overcharging.

1.3 Scope

It is usually difficult to predict the factors responsible for battery ageing and degradation. Some studies conclude the type of degradation, whether chemical or mechanical, by analyzing the battery's condition over time [29–32]. However, limited studies infer the ergonomic or environmental factors that may influence the said deterioration. This paper analyzes the trend of voltage drop of a lithium-ion battery as it discharges due to various factors and conditions. This paper aims to explore the multiple conditions contributing to faster discharging, which can be manipulated or evicted. The primary research concentrates on external factors affecting the discharge of the battery, namely, vehicle load, ground terrain, braking conditions, and temperature. To consolidate, the variation in the voltage of the battery has been investigated by varying each factor separately and a few factors simultaneously to understand the real-time impact on the battery.

This paper includes modifications in operational parameters to study their effect on vehicle efficiency, which is directly linked to the battery. The aim is to conduct testing of voltage drops under various conditions and understand the combined impact of these parameters. The present research will help predict the battery's efficiency and its dependency on external factors [33]. This study can further aid in optimizing the battery and its application to its maximum potential. The enhancement and progression of battery technologies, sustainable and manufacturable battery pack, and robust design of the battery pack act as a major catalyst in the promotion of electric vehicles as a means of transportation and energy reserve [34].

The battery under observation is lithium-ion, one of the most prominent propellers for EVs. Apart from vehicles, it finds use in solar energy storage. When these two applications are combined, it will pave the way for the energy transition that will be sustainable, economical, efficient, and convenient nonetheless [35–37]. Thus, research about lithium-ion batteries, their study, analysis, and up-gradation will be a breakthrough in achieving this conclusion.

In 2021, the automobile industry aspires to have over 50 per cent of all new models equipped with EV drivetrains [38]. This is possible as many original equipment manufacturers (OEMs) have aimed to introduce models to their production lines, which is nonetheless aided by government policies. In the coming decade, the EVs produced would comprise further optimized versions of their electronic systems due to advancements in the methods of monitoring energy consumption [39].

2 Materials and method

2.1 Materials and configuration

The main focus of this work is the lithium-ion battery. The battery used in the following analysis is an essential component of an existing project that involved the design and fabrication of a supermileage vehicle. The vehicle was conceptualized and manufactured by Team Panthera for the Shell Eco-Marathon, Asia, and is illustrated in Fig. 1. The car was designed on Solidworks software [40]. The specifications of the battery cater to the vehicle. The experimental analysis for the battery performance and voltage drop conducted later in this research has been done *via* the said supermileage vehicle. The configuration of the battery has been charted in Table 1. The authors had begun taking readings with an initial voltage of 53.4 V. The observations were taken using a voltmeter enabled in the vehicle itself. The shell vehicle consists of a compact chassis with subsystems specified in Table 2.

Figure 1: Illustration of the electric vehicle used for experimental analysis.

Table 1: Custom lithium-ion battery configuration.

Custom battery configuration	
Current rating	20 Ah
Cells arrangement	13S 8P
Rated voltage	48 V
Number of batteries	1

Table 2: Supermileage vehicle subsystems.

Chassis	Structural members: Aluminium 4130	Single passenger seat
Steering	Steering assembly	
Brake assembly	Brake pedal	Braking handle mounted on the steering
Battery	Lithium-lon battery with mount and connections	
Transmission	Acceleration system, including the pedal	
Miscellaneous	Honking system	

2.2 Method

The electrical connections of the vehicle used for the present research are illustrated in Fig. 2. The positive terminal connects the battery to the kill switch, which is externally accessible so that the vehicle can be stopped in an emergency. There are three wires connected to the motor controller. The fourth wire is a Hertz sensor which senses the frequency and sends the signal to the motor regarding the speed. The command given on the throttle is accessed by the controller and transmitted to the motor. The negative terminal connects the battery directly to the controller and speedometer. Also, the kill switch is connected directly to the speedometer and controller. The battery usually takes 5–6 h to charge to its maximum capacity. The speed reading is observed on an external speedometer software.

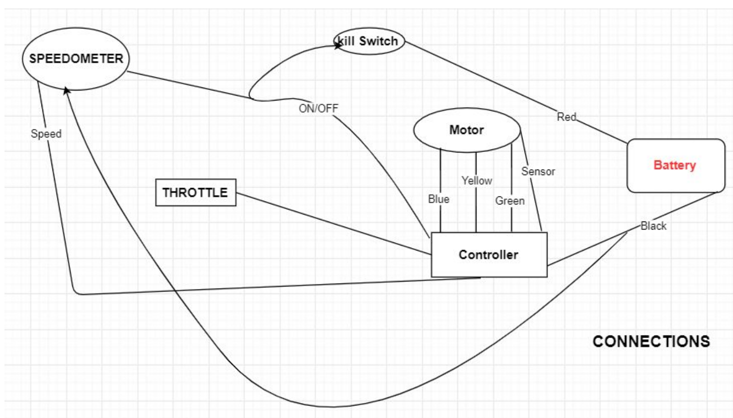

Figure 2: Illustration depicting the electrical connections of the electric vehicle.

For readings, the experiments were conducted at different times of the day to get the different environmental temperatures. Accordingly, the temperature of the battery taken and its effects were noticed. The experimentation started in the early morning when it was slightly chilly, and then based on the environment temperature, it continued to the afternoon when it was relatively hotter and then in the night when it was cold again. A thermometer was installed with the vehicle to measure the environmental temperature. Additionally, the load on the vehicle was measured from the weighing scale and varied from 49 kg to 55 kg. Also, a voltmeter was installed with the vehicle to measure the voltage drop during the experiments.

The analysis and observations have been performed from start to end on the supermileage vehicle throughout the same day. The mileage observed was approximately 119 km/kWh. The four essential parameters such as temperature, number of brakes, load and surface terrains, have been considered for experimentation as illustrated in Table 3.

Table 3: List and range of parameters evaluated during experimentation.

Parameters considered	Range defined
Temperature	6°C
Number of brakes	20 brakes
Load	6 kg
Terrain	muddy + grass, concrete

1. The first parameter, the temperature, has been varied to check the variation of the discharging of the battery. Temperature variation was achieved through changes in the temperature of the surroundings from morning to evening. The discharge at temperature differences of 2°C has been observed by keeping the load constant.

2. The second parameter, the number of brakes, has been observed by keeping the temperature, load, and distance travelled constant. The number of brakes applied is increased for a fixed distance.

3. The third parameter is load. While keeping the temperature constant and increasing the load by 6 kg, the discharge rate has been analyzed in gradual increments.

4. The final parameter, the terrain, has been changed twice to check the battery's voltage drop. The experiment was conducted on: (1) a muddy-grass road and (2) a concrete road.

3 Result and discussions

The variation of discharge with temperature, load, terrain, and the number of brakes is represented in graphs and charts for efficient visualization of results.

3.1 Temperature variation analysis

As illustrated in Fig. 3, the vehicle's voltage drops with an increase in temperature. This is associated with battery performance and its chemical reactions [41]. The initial drop is observed at 0.3 V, which is steeper till 24°C (53.8 V to 53.5 V), followed by a short phase with a reduced drop, i.e., 66% of the initial fall (53.5 V to 53.3 V). The voltage drop is observed to get steeper again (53.3 V to 53.0 V) beyond 26°C. Low temperatures show a reduction in the ionic conductivity of the battery [42, 43]. In contrast, high temperatures tend to increase the rate of thermal ageing, thereby shortening the life of the lithium-ion battery [44, 45].

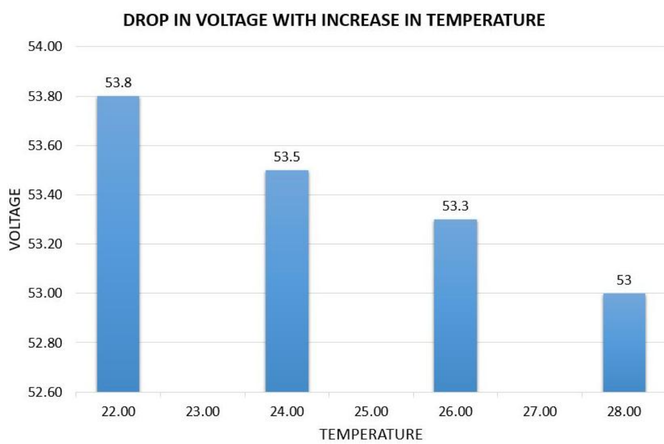

Figure 3: Battery voltage *versus* temperature in degrees Celsius to depict voltage drop with temperature.

3.2 Number of brakes variation analysis

Figure 4 shows that the voltage drop increases with the number of brakes applied due to high energy losses in the conventional braking system [46]. With nine brakes, the voltage drop is negligible, as seen from the reading change from 52.2 V to 52.1 V, i.e., 0.1 V. When the number of brakes is increased by 6 to 15 for the same distance patch, the drop observed increases by 100%, i.e., 0.2 V (from 52.1 V to 51.9 V). With another increment of 6 brakes to 21, the drop increases by another 100% to 0.4 V (from 51.9 V to 51.4 V). This doubling trend in voltage drops is inferred to be highly worrisome and causes concern in EVs. The battery powers auxiliary systems. The brakes are a crucial part of the system and have an impact on the observed voltage drop. Therefore, it is recommended to adopt energy-efficient driving practices to develop an optimal speed. This, in turn, reduces the aerodynamic drag and hence, the power consumption. Moreover, it is also recommended to install a regenerative braking system. However, existing research has proved that even with regenerative braking, optimal velocity profiles can be beneficial in reducing electromechanical energy conversion losses [47]. Several researchers have studied the benefits of regenerative braking systems in the past. Recovering the kinetic energy evolved can substantially reduce the load on the lithium-ion battery [48–52].

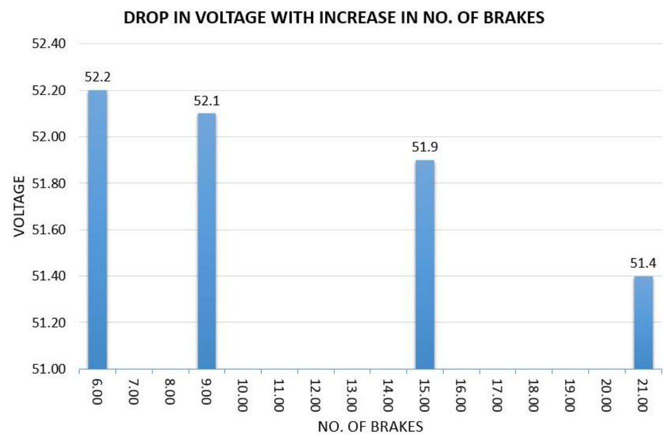

Figure 4: Battery voltage *versus* number of brakes to depict voltage drop with speed variation.

3.3 Load variation analysis

The voltage of the battery drops drastically with an increase in the load, as illustrated in Fig. 5. At 49 kg, the observed drop is 0.3 V, from 53.3 V to 53.0 V. When the load gradually increases to 55 kg, the voltage drop also

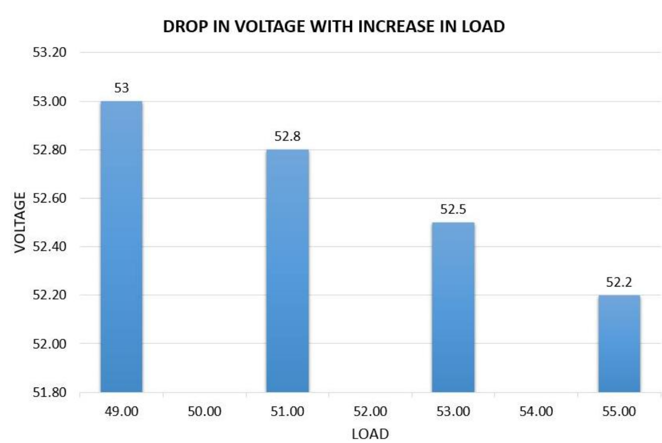

Figure 5: Battery voltage versus load in kg to depict voltage drop with load.

increases by 167% to 0.8 V, from 53.0 V to 52.2 V. This is because, as the load increases, the current through the battery resistance increases; thus, the voltage drop increases [53].

3.4 Terrain variation

The terrain was switched from muddy-grass to concrete to investigate the impact of road surface roughness on the change in voltage drop. As depicted in Table 4, the voltage drop observed for a concrete road and a muddy-grass, i.e., a relatively rugged road, was 0.1V (51.5 V to 51.4 V, and 51.4 V to 51.3 V, respectively) for the same distance with the same loading and environmental conditions. Therefore, the average drop is considered relatively the same across different terrains except for rocky and puddled terrains due to the added load on suspension and the difficulty of traction.

Table 4: Drop in voltage with variable terrain.

Terrain	Voltage drop (V)	Change in voltage (V)
Concrete	51.5 to 51.4	0.1
Muddy + Grass	51.4 to 51.3	0.1
Rocky	51.3 to 51.0	0.3

A group of researchers studied the performance of an EV powered by a lithium-ion battery in the hilly terrains of Vermont and found a 13% increase in energy consumption without regenerative braking [54]. It is safe to conclude that terrain is an essential, if not highly influential, characteristic that may impact the battery's performance.

4 Conclusions

In the present research, a lithium-ion battery, part of a competitive supermileage vehicle, has been considered. Various factors, such as vehicle load, temperature gradient, road surface terrain, and vehicle speed, have been analyzed to check the vehicle's overall performance in different operating conditions. The effect of these factors on the battery discharging rate has also been investigated. The following remarks have been concluded as mentioned below.

- From the analysis, it was observed that the discharge rate remained constant for the considered temperature difference of 6°C. However, warming a battery decreases internal resistance and improves the electrochemical reaction. Thus, operating a battery at a high temperature improves battery performance. Therefore, increasing temperature up to a limit will improve the performance. However, overheating batteries could result in thermal runaways, damaging the vehicle and its life. Therefore, batteries are often accompanied by cooling systems.

- Secondly, increasing the number of brakes increased discharge. With nine brakes, the voltage drop is negligible (0.1 V), however, when the number of brakes risen from 9 to 15 for the same distance patch, the drop observed increased to 0.2 V. With another increment of 15 brakes to 21, the drop increases further to 0.5 V. Hence, it is clear that starting increasing brakes will not impact much on the discharge rate, however, when the number of brakes increases beyond 15, the battery will discharge with a much faster rate.

- Lastly, a heavier load requires more energy to operate the electric vehicles; this voltage drop is more significant with a higher load, and hence, the battery will discharge more. Additionally, the average voltage drop is relatively the same across different terrains except for rocky and puddled terrains due to the added load on suspension and the difficulty of traction.

It is important to acknowledge the results validated by experimentation and make subsequent changes to our method of usage. By fabricating lightweight vehicles, the discharge rate may be controlled. This is achieved by smart weight-reduction strategies employed while choosing the chassis material, removing material without hampering the strength of the component, etc. Moreover, some additional measures taken to limit the discharge rate are mentioned below.

1. As recommended, keeping the tyre pressure maximum according to its model specifications.

2. Charging and discharging the battery to a moderate range of voltages. Extremely high and low voltages affect the battery life.

3. Usage at temperatures ranging between a few degrees of room temperature. At high temperatures, the electrochemical reactions that

power the battery occur at a higher rate as opposed to low temperatures, at which the chemical reaction rates reduce. Low temperature also causes low conductivity in lithium salts.

4. Reducing the number of brakes, especially abrupt braking, leads to a rapid drop in battery voltages which are otherwise quite slow in their discharge. Thus, a smoother drive at a slow-varying velocity keeps the battery from discharging soon.

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References

[1] Abas N., Kalair A., Khan N.: *Review of fossil fuels and future energy technologies.* Futures **69**(2015), 31–49. doi: 10.1016/j.futures.2015.03.003

[2] Dudley B.: *BP Statistical Review of World Energy 2019* (68th Edn.). BP p.l.c., London 2019. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf (accessed 8 Dec. 2022).

[3] Siram J., Sahoo N., Saha U.K.: *Changing landscape of India's renewable energy and the contribution of wind energy.* Clean. Eng. Technol. **8**(2022), 100506. doi: 10.1016/j.clet.2022.100506

[4] Welsby D., Price P., Pye S., Ekins P.: *Unextractable fossil fuels in a 1.5°C world.* Nature **597**(2021), 230–234. doi: 10.1038/s41586-021-03821-8

[5] Choudhary P., Sachar S., Khurana T., Jain U., Parvez Y., Soni M.: *Energy analysis of single cylinder 4-stroke diesel engine using diesel and diesel-biodiesel blends*. Int. J. Appl. Eng. Res. **13**(2018), 12, 10779–10788.

[6] Kanaujia A., Bhati M., Lakshmanan S., Nishad S. N., Bhattacharya S.: *Air Pollution in India: A Critical Assessment and Suggestive Pathways for Clean Air. A project on Studies on Contemporary Challenges*. CSIR-NIScPR Discuss. Pap. Ser., New Delhi 2022.

[7] Wallington T.J., Anderson J.E., Dolan R.H., Winkler S.L.: *Vehicle emissions and urban air quality: 60 years of progress*. Atmosphere **13**(2022), 5, 650. doi: 10.3390/atmos13050650

[8] Jain U., Khurana T., Sachar S., Choudhary P., Parvez Y.: *Performance characteristics and energy analysis of a 4-stroke single cylinder diesel engine using diesel and diesel-kerosene blends*. Int. J. Res. Anal. Rev. **5**(2018), 3, 194–203.

[9] Srivastava S., Chaubey H., Parvez Y.: *Performance evaluation of CI engine using diesel, diesel-biodiesel blends and diesel-kerosene blends through exergy analysis*. IOP Conf. Ser.-Mater. Sci. **691**(2019), 1. doi: 10.1088/1757-899X/691/1/012066

[10] Kim T.H., Park J.S., Chang S.K., Choi S., Ryu J.H., Song H.K.: *the current move of lithium ion batteries towards the next phase*. Adv. Energ. Mater. **2**(2012), 7, 860–872. doi: 10.1002/aenm.201200028

[11] Brown S., Pyke D., Steenhof P.: *Electric vehicles: The role and importance of standards in an emerging market*. Energ. Policy **38**(2010), 7, 3797–3806. doi: 10.1016/j.enpol.2010.02.059

[12] Botsford C., Szczepanek A.: *Fast charging vs. slow charging: Pros and cons for the new age of electric vehicles*. EVS24 Int. Battery, Hybrid, Fuel Cell Electric Vehicle Symp, Stavanger, May 13–16, 2009.

[13] Kalyan R., Murali V., Pitchaimuthu R.: *Coordinate control of grid power, battery soc and LVRT protection in single VSC tied DFIG*. Distrib. Gener. Alternat. Energ. J. **37**(2022), 587–608. doi: 10.13052/Dgaej2156-3306.37310

[14] Revankar S.T.: *Chemical energy storage*. In: *Storage and Hybridization of Nuclear Energy: Techno-economic Integration of Renewable and Nuclear Energy* (H. Bindra, S. Revankar, Eds.). Elsevier, 2019, 177–227. doi: 10.1016/b978-0-12-813975-2.00006-5

[15] Shastri S., Parvez Y., Chauhan N.R.: *Wireless power transfer system for scorbot Er-4u robotic arm*. Int. J. Power Energ. Sys. **40**(2020), 3, 103–111. doi: 10.2316/J.2020.203-0044

[16] Harks P.P.: *Characterization and development of high energy density Li-ion batteries*. TU Delft, 2019. doi: 10.4233/uuid:cab44efd-8a4c-4b4d-8168-bd64738adb64 (accessed 8 Dec. 2022).

[17] Salunke A.D., Chamola S., Mathieson A., Boruah B.D., Volder M.D., Ahmad S.: *Photo-rechargeable Li-Ion batteries: device configurations, mechanisms, and materials*. ACS Appl. Energ. Mater. **5**(2022), 7, 7891–7912.

[18] Whittingham M.S.: *Introduction: Batteries*. Chem. Rev. **114**(2014), 23, 11413. doi: 10.1021/cr500639y

[19] Mekonnen Y., Sundararajan A., Sarwat A.I.: *A review of cathode and anode materials for lithium-ion batteries*. Southeast Conf. 2016, Norfolk, (2016), 1–6. doi: 10.1109/secon.2016.7506639

[20] Oswal M., Paul J., Zhao R.: *A Comparative Study of Lithium-Ion Batteries*. Univ. of Southern California, 2010.

[21] Situ L.: *Electric vehicle development: The past, present & future*. In: Proc. 3rd Int. Conf. on Power Electronics Systems and Applications (PESA), 2009, 1–3.

[22] Koshika K., Suzuki H.: *Performance survey for Li-Ion battery in a hybrid vehicle with 105,000 km driving*. In: Abstr. ECS Meet. **MA2020-02**, 2020, 1051. doi: 10.1149/MA2020-0261051mtgabs

[23] Husain M.A., Rajput R., Gupta M.K., Tabrez M., Ahmad M.W., Bakhsh F.I.: *Design and implementation of different drive topologies for control of induction motor for electric vehicle application*. Distrib. Gen. Altern. Energ. J. **37**(2022), 4, 999–1026. doi: 10.13052/dgaej2156-3306.3746

[24] Miao Y., Hynan P., Jouanne A.V., Yokochi A.: *Current Li-Ion battery technologies in electric vehicles and opportunities for advancements*. Energies **12**(2019), 6, 1074. doi: 10.3390/en12061074

[25] Wang C., Chen Y., Zhang Q., Zhu J.: *Dynamic early recognition of abnormal lithium-ion batteries before capacity drops using self-adaptive quantum clustering*. Appl. Energ. **336**(2023), 120841. doi: 10.1016/j.apenergy.2023.120841

[26] Goodenough J., Kim Y.: *Challenges for rechargeable Li batteries*. Chem. Mater. **22**(2010), 3, 587–603. doi: 10.1021/cm901452z

[27] Huang Z., Liu J., Zhai H., Wang O.: *Experimental investigation on the characteristics of thermal runaway and its propagation of large-format lithium ion batteries under overcharging and overheating conditions*. Energy **233**(2021), 121103. doi: 10.1016/j.energy.2021.121103

[28] Dar U., Siddiqui A.S., Bakhsh F.I.: *Design and control of an off board battery charger for electric vehicles*. Distrib. Gen. Altern. Energ. J. **37**(2022), 4, 959–978. doi: 10.13052/dgaej2156-3306.3744

[29] Seruga D., Gosar A., Sweeney C.A., Jaguemont J., Mierlo J.V., Nagode M.: *Continuous modelling of cyclic ageing for lithium-ion batteries*. Energy B **215B**(2021), 119079. doi: 10.1016/j.energy.2020.119079

[30] Ge M.F., Liu Y., Jiang X., Liu. J.: *A review on state of health estimations and remaining useful life prognostics of lithium-ion batteries*. Measurement **174**(2021), 109057. doi: 10.1016/j.measurement.2021.109057

[31] Chandran V., Patil C.K., Karthick A., Ganeshaperumal D., Rahim R., Ghosh A.: *State of charge estimation of lithium-ion battery for electric vehicles using machine learning algorithms*. World Elect. Veh. J. **12**(2021), 38, 1–17. doi: 10.3390/wevj12010038

[32] García A., Serrano J.M., Boggio S.M., Golke D.: *Energy assessment of the ageing phenomenon in Li-Ion batteries and its impact on the vehicle range efficiency*. Energ. Convers. Manage. **276**(2023), 116530. doi: 10.1016/j.enconman.2022.116530

[33] Xiong R., Pan Y., Shen W., Li H., Sun F.: *Lithium-ion battery aging mechanisms* Renew. Sust. Energ. Rev. **131**(2020), 110048. doi: 10.1016/j.rser.2020.110048

[34] Canteros M.L., Polansky J.: *Study of the heat pump for a passenger electric vehicle based on refrigerant R744*. Arch. Thermodyn. **43**(2022), 2, 17–36. doi: 10.24425/ather.2022.141976

[35] Chen T., Jin Y., Lv H., Yang A., Liu M., Chen B., Chen Q.: *Applications of lithium-ion batteries in grid-scale energy storage systems*. T. of Tianjin Univ. **26**(2020), 208–217. doi: 10.1007/s12209-020-00236-w

[36] Singh D., Chaubey H., Parvez Y., Monga A., Srivastava S.: *Performance improvement of solar PV module through hybrid cooling system with thermoelectric coolers and phase change material*. Sol. Energy **241**(2022), 538–552. doi: 10.1016/j.solener.2022.06.028

[37] Zhou Y., Wang F., Xin T., Wang X., Liu Y., Cong L.: *Discussion on international standards related to testing and evaluation of lithium battery energy storage*. Distrib. Gen. Altern. Energ. J. **37**(2022), 3, 435–448. doi: 10.13052/dgaej2156-3306.3732

[38] Lane B.W., Betts N.M., Hartman D., Carley S., Krause R.M., Graham J.D.: *Government promotion of the electric car: Risk management or industrial policy?*. Eur. J. Risk Regul. (EJRR) **4**(2013), 2, 227–245.

[39] Valle J.A.D., Viera J.C., Ansean D., Branas C., Luque P., Mantaras D.A., Pulido Y.F.: *Design and validation of a tool for prognosis of the energy consumption and performance in electric vehicles*. Transp. Res. Proc. **33**(2018), 35–42. doi: 10.1016/j.trpro.2018.10.073

[40] Planchard D.: *Solidworks 2018 Reference Guide*. (2018). https://files.solidworks.com/partners/pdfs/referenceguide.pdf (accessed 8 Dec. 2022).

[41] Lu Z., Yu X.L., Wei L.C., Cao F., Zhang L.Y., Meng X.Z., Jin L.W.: *A comprehensive experimental study on temperature-dependent performance of lithium-ion battery*. Appl. Therm. Eng. **158**(2019), 113800. doi: 10.1016/j.applthermaleng.2019.113800

[42] Bandhauer T.M., Garimella S., Fuller T.F.: *A critical review of thermal issues in lithium-ion batteries*. J. Electrochem. Soc. **158**(2011), 3, R1–R5. doi: 10.1149/1.3515880

[43] Kong J., Yang F., Zhang X., Pan E., Peng Z., Wang D.: *Voltage-temperature health feature extraction to improve prognostics and health management of lithium-ion batteries*. Energy **223**(2021), 120114. doi: 10.1016/j.energy.2021.120114

[44] Ma S., Jiang M., Tao P., Song C., Wu J., Wang J., Shang W.: *Temperature effect and thermal impact in lithium-ion batteries: A review*. Pr. Nat. Sci. Mater. Int. **28**(2018), 6, 653–666. doi: 10.1016/j.pnsc.2018.11.002

[45] Liu G., Ouyang M., Lu L., Li J., Han X.: *Analysis of the heat generation of lithium-ion battery during charging and discharging considering different influencing factors*. J. Therm. Anal. Calorim. **116**(2014), 1001–1010. doi: 10.1007/s10973-013-3599-9

[46] Miri I., Fotouhi A., Ewin N.: *Electric vehicle energy consumption modelling and estimation – A case study*. Int. J. Energ. Res. **45**(2020), 501–520. doi: 10.1002/er.5700

[47] Han J., Vahidi A., Sciarretta A.: *Fundamentals of energy efficient driving for combustion engine and electric vehicles: An optimal control perspective*. Automatica **103**(2019), 558–572. doi: 10.1016/j.automatica.2019.02.031

[48] Gao Y., Chen L., Ehsani M.: *Investigation of the effectiveness of regenerative braking for EV and HEV*. SAE Transactions **108**(1999), 3184–190. doi: 10.4271/1999-01-2910

[49] Cikanek S.R., Bailey K.E.: *Regenerative braking system for a hybrid electric vehicle*. In: Proc. 2002 Am. Control Conf. (ACC) (IEEE Cat. No. CH37301), **4**(2002), 3129–3134. doi: 10.1109/ACC.2002.1025270

[50] Yoong M., Gan Y., Gan G., Leong C., Phuan Z., Cheah B., Chew K.: *Studies of regenerative braking in electric vehicle*. IEEE Conf. on Sustainable Utilization and Development in Engineering and Technology, Kuala Lumpur, 2010, 40–45. doi: 10.1109/student.2010.5686984

[51] Fatima N., Mustafa J.: *Production of electricity by the method of road power generation*. Int. J. Adv. Elect. Electron. Eng. **1**(2016), 1, 9–14.

[52] Raj A., Verma A., Joshi H., Gupta M., Mustafa J.: *Generation of electricity by crank mechanism method in railway track*. In: Proc. Int. Conf. on Computational and Experimental Methods in Mechanical Engineering (ICCEMME 2017), Greater Noida 8–9 Dec. 2017, 326–330.

[53] Morcos M.M., Dillman N.G., Mersman C.R.: *Battery chargers for electric vehicles*. IEEE Power Eng. Rev. **20**(2000), 11, 8–11. doi: 10.1109/39.883280.

[54] Michael C., Keith P., Walter V.: *Performance of a Battery Electric Vehicle in the Cold Climate and Hilly Terrain of Vermont-Final Report*. Transp. Res. Cent. Res. Rep. **258**, Univ. of Vermont, Burlington 2008. https://rosap.ntl.bts.gov/view/dot/34424/dot_34424_DS1.pdf (accessed 8 Dec. 2022).