X. Dorronsoro, I. Lopetegi, E. Garayalde, U. Iraola and J. Yeregui, "Modular Battery Energy Storage Systems for Available Energy Increase," 2022 IEEE Vehicle Power and Propulsion Conference (VPPC), Merced, CA, USA, 2022, pp. 1-7.

DOI: https://doi.org/10.1109/VPPC55846.2022.10003430

Modular Battery Energy Storage Systems for Available Energy Increase

Xabier Dorronsoro
Faculty of Engineering
Mondragon Unibertsitatea
Mondragon, Spain
xdorronsoro@mondragon.edu

Iker Lopetegi
Faculty of Engineering
Mondragon Unibertsitatea
Mondragon, Spain
ilopetegui@mondragon.edu

Erik Garayalde
Faculty of Engineering
Mondragon Unibertsitatea
Mondragon, Spain
egarayalde@mondragon.edu

Unai Iraola
Faculty of Engineering
Mondragon Unibertsitatea
Mondragon, Spain
uiraola@mondragon.edu

Josu Yeregui
Faculty of Engineering
Mondragon Unibertsitatea
Mondragon, Spain
jyeregui@mondragon.edu

Abstract—The aim of this work is to dive into the available energy of different configurations of battery packs, a vital factor when it comes to improving the driving range of electric vehicles. To that end, two different storage system topologies are considered: non-modular and modular batteries. Each of them with passive or active balancing strategies. To achieve realistic results, a reduced-order electrochemical model is used. Cell-to-cell capacity variations are introduced to represent non-uniformities inside the battery packs. Although many different capacity distributions might be considered, the scope of this paper has been limited to classical normal distribution. The results of this analysis show that the available energy can be increased using modular battery solutions.

Index Terms—Battery-pack, Available energy, Cell consistency, Modular battery, Physics-based model.

I. Introduction

ONE of the main challenges in this regard for electric vehicles (EV) is the lack of consistency among the parameters of all the cells. This non-uniformity is measurable and is usually represented in factors such as capacity, internal resistance and thermal properties. This leads to the lessening of the total amount of available energy of the battery pack (BP), always limited by the weakest cell [1]. Thus, in medium and large size battery systems, a high percentage of the available energy will be unused due to cells' inhomogeneities. In the context of EV, this is understood as a constraint in the driving range, a crucial characteristic towards its full adoption.

When developing these BESSs for EVs, features such as scalability and reusability are not always taken into account. For this reason, despite been constructed in separated modules physically, at the end, all of them operate as a single BP unit. However, to counter issues related to their lack of robustness, multiple degradation and aforementioned inconsistency problems are prevented by using external balancing circuits and oversizing [1], [2].

On the one hand, as a way to be able to handle this unbalances, passive and active balancing strategies are the most well-known solutions [3], [4]. According to the literature, the former is commonly based on the most charged cell's energy dissipation with the aim of achieving total equalization at the end-of-charge. Regarding the latter option, traditionally, it has been focused on the balancing of the state of charge (SoC) by redistributing charge during the battery cycles. Nevertheless, for the purpose of balancing some other measurable characteristics like losses minimization, thermal balancing and power capability equalization, smart balancing systems are already being developed [5].

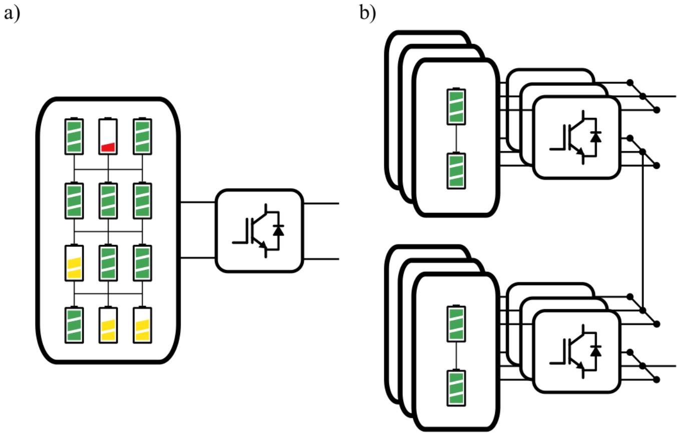


Fig. 1. BESS configurations for DC a system a) conventional BP structure b) modular battery system.

On the other hand, the increase in the volume and the cost for oversizing are handicaps that are being tried to be solved, among other things, by introducing the concept of modular BESSs, e.g. in Fig. 1. Modularity enables characteristics such as the reusability of the design and even the repair or replacement of any faulty component. At the same time, modular solutions may provide enhancements like performing active thermal distribution control strategies and active cell/module balancing algorithms, while reducing power and voltage stress in the power electronic devices [6]–[8]. Besides the technical advantages that a modular system present, it may also contribute in the increase of the reliability of the battery [9]. All this could be translated into considerable financial savings for the operator of the system.

In order to calculate the available energy of a battery pack during discharge, first, accurate estimations of the available energy of the cells is needed. For these calculations, a physics-based reduced-order model (ROM) is used. Since the physics-based ROM is a faithful representation of the cells, their calculated accessible energy depends on their discharge current. In consequence, the calculated available energy of the battery pack also depends on the applied current, which makes the analysis more precise.

As mentioned above, when analysing the available energy of a battery system during the discharge process, establishing the cells' initial capacity as well as the corresponding cell-to-cell variation is mandatory [10]. As already stated in literature, this values can vary due to many reasons and in different ranges [11]. All these variations have to fit with a kind of distribution so they can be implemented in simulations. In the literature there is not such a wide research focused on which distribution is the appropriate. That is why the normal distribution as the one presented in [3] is the most classical option.

The contribution of this article is focused on the increase of the accessible energy of any BP oriented towards EVs. To this end, a comparison between the traditional battery systems and new modular battery storage systems is performed. Active and passive balancing are considered as methods to tackle the capacity deviation represented by means of a normal distribution.

To carry out this research the paper is planned in four main sections. It starts by presenting the reduced-order electrochemical model corresponding to the cell in Section II. Then, the BP models together with the consistency issues are explained in the Section III. Once all the theoretical frameworks are introduced, the obtained available energy results are shown in Section IV. Lastly, to sum up this work, some brief conclusions and future research lines are proposed in Section V.

II. Cell modelling

The cells that are used in this study are the LG M50. As it has been stated previously, in this study the cell voltage and the discharge capacity are not obtained from their nominal values. Instead, the capacity and the voltage are calculated using a cell model. This way, the obtained results for the accessible energy study are more realistic, since they include the cell current dependency.

Different modeling approaches could be considered for this work, such as empirical models for example. With an empirical model, the cell voltage response and the discharge capacity can be calculated for each SoC and current case. However, physics-based models (PBMs) have been preferred to model the cells. Apart from the voltage and capacity calculations, PBMs can represent the internal physicochemical behavior of the cell, which can be used to add detailed physical aging models or thermal models. These are not included in this study, but they are considered to be an interesting topic of research in this field, and may be added in future work.

Among the different PBMs that can be used for cell modeling, we selected the pseudo-two-dimensional (P2D) model [12], [13]. The model selection requires a trade-off between the represented amount of detail and the computational cost. The P2D model is a continuum-scale physics-based model, and it describes the electrochemical processes occurring inside a Li-ion battery cell using a partial differential algebraic equation (PDAE) system [14]. Different methods may be used to solve the PDAE system: finite element method (FEM), finite volume method, finite difference method, etc. However, the differential algebraic equation system obtained from these methods are expensive computationally, and therefore, not the best ones for this analysis, where a big amount of simulations are required. For this reason, a more computationally efficient numerical method has been used to solve the system: the orthogonal collocation on Chebyshev polynomials [15]. Using this method we obtained the ROM that we used for the accessible energy analysis.

The ROM has been validated comparing its results to a full-order model solution that has been obtained using FEM in COMSOL Multiphysics ®. With the orthogonal collocation method, the computational time was reduced by a factor of 20, and the root mean square (RMS) error was under 1 mV for a 1C discharge. The parameters of the LG M50 cell for the simulations have been obtained from [16].

III. Battery-pack modelling

The study of the available energy is always a hot topic in the application of EVs due the concern with extending the driving range. In this context, a model to approach the energy provided by a BESS is suggested in [3]. However, this analysis focuses on the comparison of non-modular BPs with one converter per cell topologies. This research has been extended with modular BP solutions in our previous work in [17] based on nominal cell values, regardless the effect of the Crate in the performance of any cell. So as to increase the accuracy of the results, this article focuses on the analysis of non-modular and modular topologies with electrochemical cell models.

A. Cell-to-cell Consistency

Once the cell model is developed, the next step before the estimation of the available energy of the BP is to model and determine the cell-to-cell variations and inhomogeneities. As it is well known, there are many factors such as the material inconsistencies as well as manufacturing process issues that result in differences between cells. Moreover, nonidentical environmental and operational characteristics may also boost cell-to cell variations [18]. That in mind, any inconsistency between the cells becomes a vital factor regarding the performance of the BP.

According to the literature, in [19] the available energy of the BP is reduced by 25% due to a maximum SoC deviation of 7%. In [20], the initial capacity of 700 cells is measured in order to define the initial charge model by means of a bimodal distribution or two separated Gaussian distributions. The research carried out in [21] is grounded on a SoC variation of 5% with an initial SoC of 95% that follows a normal distribution. A wider range of SoC, up to 34%, is considered in [22].

Taking into account the impact of cell inconsistencies in the final useful energy estimation, it is considered mandatory not to ignore its characterisation. Therefore, based on examples of the literature and the EV application, an average SoC of 80% is assumed with a normal distribution that reaches a maximum standard deviation of 9%. Hence, this research explores the available energy under the influence of different SoC variations. The essential parameters are presented in the Tab. I.

B. Non-modular systems

1) Passive balancing BP: The available energy of conventional BPs with passive balancing (E$_{pb}$) is going to be limited always by the weakest cell (operation during discharge cycles is neglected). This maximum energy supply is estimated by using Eq. 1, as the balancing energy losses and the converter efficiency are neglected for this topology. The corresponding circuit is shown in Fig. 1a.

$$E_{pb} = \sum_{n=1}^{N} \int_0^T v_n(t) i_{dch}\, dt \tag{1}$$

2) Active balancing BP: With the aim of increasing the available energy, active balancing circuits give to the whole BP the ability manage SoC unbalances. Thus, theoretically this system can always provide more energy in comparison with the aforementioned non-modular passive balancing circuit. Fig. 2b represents the schematic that has been considered. It has to be taken into account that any balancing circuit is under the influence of the efficiency issues (represented with a resistance R$_b$).

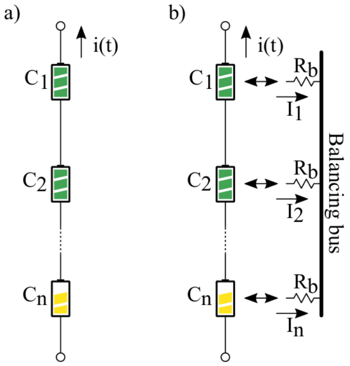


Fig. 2. Conventional battery-systems a) Passive balancing b) Active balancing.

During the discharge cycle of the BP, two different situations must be contemplated: 1) the estimated time before the cut-off voltage is achieved does not limit the maximum balancing current, meaning that non-uniformities are solved successfully 2) as a consequence of high discharge current there is not enough time to finish the equalization without exceeding the maximum design current; therefore, the overcurrent is solved by limiting the flowing current to the maximum of the active balancing circuit. Moreover, it has to be taken into account that the sum of the the power flow in the balancing bus has to be equal to 0. However, the calculation is simplified by assuming always nominal cell voltage and assuming an 100% efficiency when analysing this constraint. That in mind, the restriction is replaced by Kirchhoff's Law (sum of all the currents has to be equal to 0). Hence, the energy calculation can be written as presented in Eq. 2.

$$E_{ab} = \sum_{n=1}^{N} \int_0^T v_n(t)(i_{dch} + i_{b_n})\, dt - \sum_{n=1}^{N} \int_0^T i_{b_n}^2 r_b\, dt \tag{2}$$

where the balancing current i$_b$ is going to be defined by the Eq. 3. In case the maximum balancing current i$_{max}$ is achieved a correction factor β has to be applied (check the Appendix A). It has to be taken into account that the discharge time is always limited by θ, the inverse of the initial SoC condition.

$$i_b = \begin{cases} \left(\frac{\sum_{n=1}^{N} C_n}{N} - C_n\right) C_{rate}\theta\beta & \max(\left|i_{b,[1:N]}\right|) > i_{max} \\ \left(\frac{\sum_{n=1}^{N} C_n}{N} - C_n\right) C_{rate}\theta & \max(\left|i_{b,[1:N]}\right|) \leq i_{max} \end{cases} \tag{3}$$

C. Modular battery system

1) Variable balancing BP: The systems with variable balancing configurations are those that have a converter per cell, as it is shown in Fig. 3a. It is the circuit whereby individual cell charge/discharge current management is enabled. Nevertheless, each converters efficiency will impact in the resulting accessible energy, represented by R$_d$ in Fig. 3a.

With regard to the maximum available energy of a variable balancing BP (E$_{vb}$), the Eq. 4 defines the maximum supplied energy.

$$E_{vb} = \sum_{m=1}^{M} \int_0^T v_m(t) i_m\, dt - \sum_{m=1}^{M} \int_0^T r_d i_m^2\, dt \tag{4}$$

where r$_d$ estimates the losses of the converters, while M is the total amount of modules (equal to number of cells in this design) and i$_m$ is the discharge current, directly

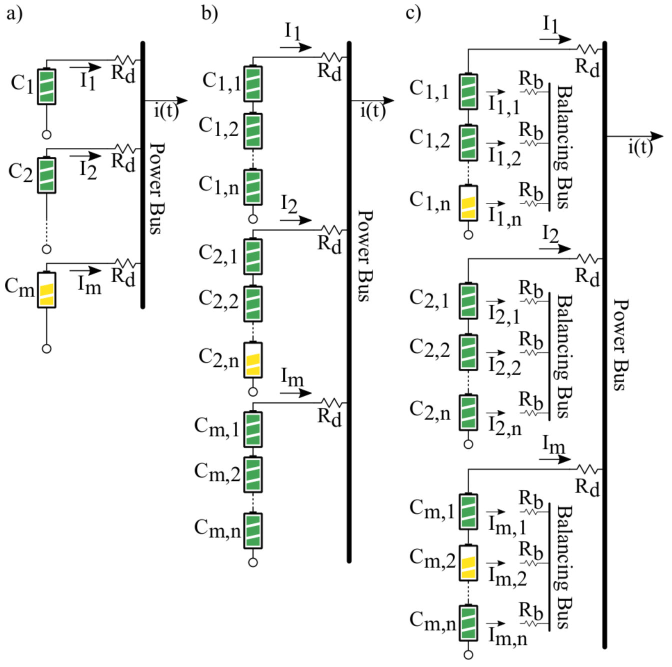


Fig. 3. Modular battery systems a) Variable balancing b) Variable + passive balancing c) Variable + active balancing.

dependent on each of the cell's and the whole system's capacity. This discharge current is determined using Eq. 5, being $C_{m_{min}}$ the weakest cells' capacity of each module.

$$i_m = \frac{C_{m_{min}}}{\sum_{m=1}^{M} C_{m_{min}}/M} C_{rate} C_{nom} \tag{5}$$

2) Modular passive balancing BP: By means of a modular BP based on passive balancing circuits, such as the one of the Fig. 3b, according to [17] higher energy levels could be supplied. At the end, the weakest cell will not limit the accessible energy of the remaining modules. Furthermore, although the available energy is not as high as in variable balancing topologies, from a hardware complexity point of view its development is more feasible.

This kind of modular designs require a detailed analysis in order to be able to consider all the possible cell combinations into the modules. However, to simplify this analysis, instead of considering each different option, the most energy limiting cases are taking into account: 1) the maximum available energy is achieved in the case where the low capacity cells are joined together in the same module, while the high capacity cells are joined in another module; 2) the minimum available energy is calculated considering the case where the cells with the lowest capacity are connected to the cells with the higher capacity in the same module. The total available energy is estimated based on Eq. 6.

$$E_{mpb} = \sum_{m=1}^{M}\sum_{n=1}^{N/M}\int_{0}^{T} v_n(t) i_m \, dt - \sum_{m=1}^{M}\int_{0}^{T} r_d i_m^2 \, dt \tag{6}$$

3) Modular active balancing BP: Similarly to the previous solution with modular passive balancing, a modular BP can also be designed with an active balancing BMS. This enables the capability to handle cell-to-cell SoC variances of each module, in order to be able to boost useful energy. Eq. 7 shows how to estimate the energy that can be provided with such systems.

$$\begin{aligned} E_{mab} = \sum_{m=1}^{M} \Bigg(& \sum_{n=1}^{N/M}\int_{0}^{T} v_n(t)\left(i_{deh,n} + i_{b,[m,n]}\right) dt \\ & - \sum_{n=1}^{N/M}\int_{0}^{T} {i_{b,[m,n]}}^2 r_b dt \Bigg) - \sum_{m=1}^{M}\int_{0}^{T} r_d i_m^2 \, dt \end{aligned} \tag{7}$$

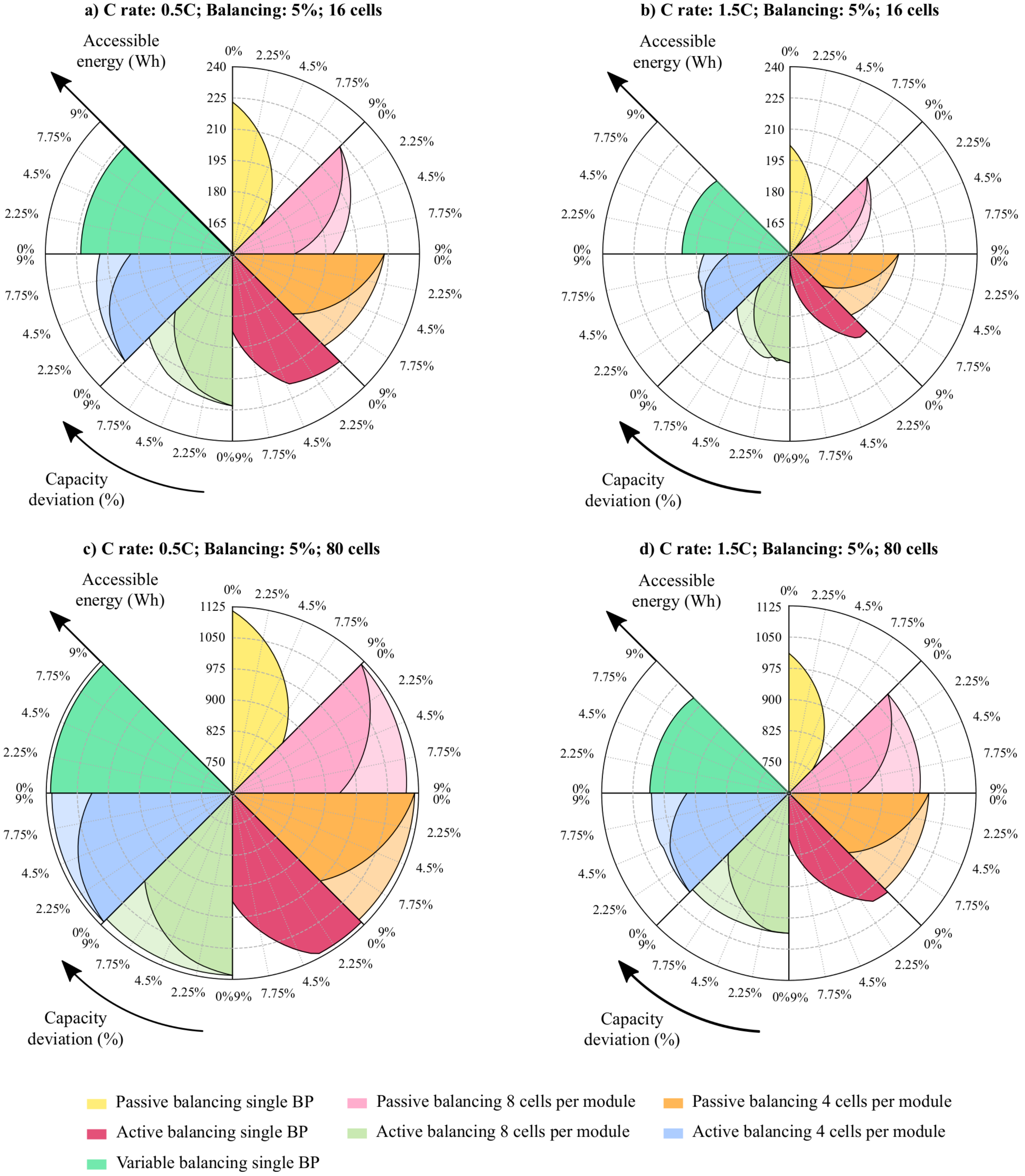
In respect of the distribution of the cells into the modules, not to analyse all the cell initial state combinations as stated in Section III-C2, the research is only focused on the estimation of the minimum and maximum available energy results. Regarding the equalization currents, following the steps of the Section III-B2, although power balance between the input and the output has to be always achieved, constant voltage is considered. As a results, balancing current inflows and outflows are again simplified to Kirchhoff's Law. At the same time, in case the balancing current of any of the cells exceeds the allowed peak value it is mandatory to apply limiting controls of Eq. 3.

IV. Results

Once the theoretical context at cell level and module level is introduced, MATLAB® is used to develop all the simulations. Thus, available energy results at different scenarios are estimated. All the required parameters are shown in Tab. I. On the one hand, different discharge currents together with various balancing currents are analyzed. On the other hand, the effect of increasing the number of cells from 16 to 80 is studied with the aim of understanding if there is any variation, and how could this affect in the context of an electric vehicle and its driving range.

Building on the defined parameters, Fig. 4 illustrates the results obtained at 0.5 C and 1.5C with a balancing current of 5% of the maximum cell capacity for systems with 16 and 80 cells. It is essential to remember that balancing system's input/output power is simplified to current equilibrium. Moreover, for a better understanding, take into account that the nominal available energy of a cell is around 18.3 Wh. In the case of a system with 16 cells, it is possible to appreciate three main considerations:

- Regardless the discharge current of the BP, the modular passive balancing solution always improves the non-modular topology as shown in Fig. 4a and


a) C rate: 0.5C; Balancing: 5%; 16 cells

b) C rate: 1.5C; Balancing: 5%; 16 cells

c) C rate: 0.5C; Balancing: 5%; 80 cells

d) C rate: 1.5C; Balancing: 5%; 80 cells

Fig. 4. Available energy ranges for different BP topologies with a balancing system of 5% of the cell capacity a) 16 cells discharge at 0.5 C b) 16 cells discharge at 1.5 C c) 80 cells discharge at 0.5 C d) 80 cells discharge at 1.5 C.

Fig. 4b. In the worst case, with a 1.5C discharge current, the traditional system's available energy is limited to 151.06 Wh, while this value increases between 10.01 Wh and 26.86 (1-2 extra cells) for

TABLE I
Data used for the simulation.

Parameters	Values
Cell name	LG M50
Cell capacity (C_{nom})	5.09 Ah
Nominal voltage	3.6 V
Maximum cell voltage	4.2 V
Minimum cell votalge	2.5 V
SoC average (θ)	80%
Standard deviation	10%
Number of cells	16 and 80
Cells per module	4 and 8
Discharge currents	0.5C and 1.5 C
Maximum balancing current	0.05 C
Balancing resistance (r_b)	0.8 mΩ
Converter resistance (r_d)	108 mΩ

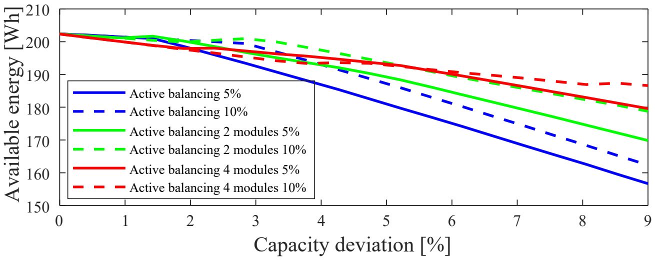
a system with 2 modules and 20.19 Wh to 40.38 Wh (2-3 extra cells) for a system with 4 modules. Lower discharge currents, such as 0.5C, provide more energy due to the effect of the C rate over the cell, however the previously mentioned accessible energy improvement is preserved.

- For the case of active balancing solutions, according to 4a and 4b, for low capacity deviations the useful energy levels are close to each other. But if a higher capacity variance has to be managed, in some cases, there may not be enough equalization time if maximum balancing constraint is complied. That in mind, the results obtained with 16 cells at a discharge current of 1.5C and a balancing current of 5% of the capacity show that, with the maximum capacity deviation, modular topologies boost the non-modular energy value between 9.9 Wh (1 extra cell) and 26.98 Wh (2 extra cells) for a 2 modules system, and 20.27 Wh (2 extra cell) and 40.46 Wh (3 extra cells) for a 4 modules BP. This results change when the discharge and balancing current relation varies. Thus, the results with 0.5C of discharge and 5% of equalization prove how favourable could be reducing the operating current flow without changing the balancing one.
- In order to access more stored energy, the variable balancing topology presents the best results. The minimum accessible energy at a 0.5C discharge is of 223.09 Wh, which is over any result of the rest of topologies. Even if the discharge power is elevated to 1.5C, handling each cells' energy individually allows rising the useful energy to 200.05 Wh over the other six topologies.

Understanding how these results are influenced by incrementing the size of the BP is also analyzed. The effects are shown in Fig. 4c and Fig. 4d. Hence, studying a system with 80 cells (BP 5 times bigger) strengths and weaknesses are accentuated from a Wh proint of view. As an example, bearing the worst capacity deviation in mind, modular passive balancing solutions ensure at least the same available energy of the non-modular active topology at 0.5 C. Instead, at 1.5 C the modular passive BP can provide at least an extra energy equal of 55.99 Wh (4 extra cells) for 8 cells modules, and 94.64 Wh (6 extra cells) for 4 cells modules. In the case of modular batteries with active balancing, better results are obtained for both discharge currents. Thus, for a C rate of 0.5C they guarantee a minimum extra energy equal to 37.81 Wh (3 extra cells) for the biggest modules and 77.65 Wh (5 extra cells) for the smallest modules. At 1.5 C the results show an improvement of the available energy of 98.03 Wh (6 extra cells) and 137.11 Wh (8 extra cells) respectively.

Furthermore, for a better comprehension of the relationship between the discharge and the balancing current, Fig. 5 is illustrated. On the one hand, Fig. 5a presents the minimum accessible energies for different capacity deviation values. On the other hand, Fig. 5b shows the maximum available energy for different cell-to-cell capacity variations. On the basis of the former figure, it is shown that doubling the balancing current enhances the capability to solve non-uniformities of capacity increasing the available energy at the end-of-discharge. The same cannot be said for the maximum accessible energy since the 4 cell per module topology does not improve its performance. Hence, an optimized active balancing system can improve even more the available energy range of the Fig. 4, particularly in modular configurations with medium to high number of cells.

a) Minimum available enegy curves



b) Maximum available energy curves

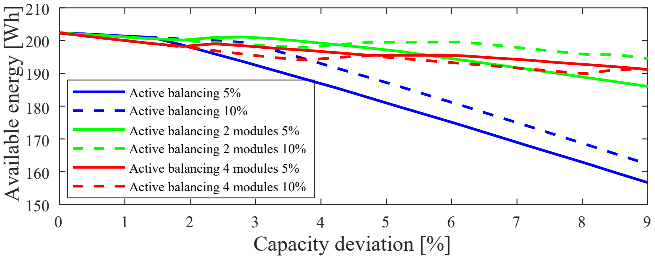


Fig. 5. Effect of the balancing current, 5% and 10% of the cell capacity, at 1.5 C discharge a) minimum available energy and b) maximum available energy.

V. Conclusions

In this paper the available energy of a BP has been explored considering modular and non-modular topologies. For the representation of the cells, a physics-based

ROM has been implemented. To enhance the quality of the results, cell-to-cell variations' influence in the performance of the system is analyzed. By means of this research the following conclusions are drawn.

The results show that modular battery topologies in the worst possible scenario can provide almost the same energy of a non-modular BP. For the rest of the situations, modular systems enable a larger driving range for an electric vehicle. This means that a transition towards modular BP solutions would improve the performance of every BESS. Comparing the different modular topologies from the available energy point of view, modules with active balancing are the best choice. They present better characteristics than a passive modular option, while simplifying the costly design of variable modular BPs. Nevertheless, in a real EV application, a trade-off between accessible energy, complexity, cost and volume have to be analyzed.

Building on the aforementioned results, the maximum equalization current requires an special attention. Although initially it is supposed to be beneficial to enable the option of fast balancing, if the cells are already operating close to their maximum C rate, balancing can be an issue in the improvement of the performance of the BP. On the other hand, in low discharge current systems, high balancing rates are not required, boosting the final results of the system. Therefore, when defining the maximum balancing current for active equalization solutions, its interaction with the discharge current should be considered to optimize the driving range of any EV.

Regarding the improvements and future lines of this study, three main aspects have to be mentioned. Firstly, developing a simulation using MATLAB Simulink® could be interesting in order to apply dynamic control systems that include cell degradation models. In addition, designing prototypes with the aim of validating the already estimated results is vital for the veracity of this analysis. Lastly, carrying out an optimization analysis to minimize the cost of the Wh is mandatory to decrease the final cost of an EV.

Acknowledgment

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A
Active Balancing Strategy

$$\alpha_1 = I_{n,bal} > 0 \tag{8}$$

$$\alpha_2 = I_{n,bal} < 0 \tag{9}$$

$$I_{pos} = \sum_{n=1}^{N} (\alpha_{1,n} I_{n,bal}) \tag{10}$$

$$I_{neg} = \sum_{n=1}^{N} (\alpha_{2,n} I_{n,bal}) \tag{11}$$

$$\beta = \begin{cases} \frac{i_{neg}}{|i_{pos}|}\alpha_1 + \alpha_2 & I_{pos} > I_{neg} \\ \frac{i_{pos}}{|i_{neg}|}\alpha_1 + \alpha_2 & I_{pos} < I_{neg} \end{cases} \tag{12}$$

References

[1] S. Rothgang, T. Baumhofer, and D. U. Sauer, "Diversion of aging of battery cells in automotive systems," in 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), 2014, pp. 1–6.

[2] T. Terlouw, T. AlSkaif, C. Bauer, and W. van Sark, "Multi-objective optimization of energy arbitrage in community energy storage systems using different battery technologies," Applied Energy, vol. 239, pp. 356–372, 2019.

[3] D. F. Frost, Battery management systems with active loading and decentralised control, 2017.

[4] N. Ghaeminezhad, Q. Ouyang, X. Hu, G. Xu, and Z. Wang, "Active cell equalization topologies analysis for battery packs: A systematic review," IEEE Transactions on Power Electronics, vol. 36, no. 8, pp. 9119–9135, 2021.

[5] J. Barreras, D. Frost, and D. Howey, "Smart balancing systems: An ultimate solution to the weakest cell problem?" IEEE Vehicular Technology Society Newsletter, 2018.

[6] M. Quraan, T. Yeo, and P. Tricoli, "Design and control of modular multilevel converters for battery electric vehicles," IEEE Transactions on Power Electronics, vol. 31, no. 1, pp. 507–517, 2016.

[7] A. M. Divakaran, D. Hamilton, K. N. Manjunatha, and M. Minakshi, "Design, development and thermal analysis of reusable li-ion battery module for future mobile and stationary applications," Energies, vol. 13, no. 6, 2020.

[8] Y. Li and Y. Han, "Evaluation of a module-integrated distributed battery energy storage system," in 2015 IEEE Energy Conversion Congress and Exposition (ECCE), 2015, pp. 1351–1358.

[9] X. Dorronsoro, E. Garayalde, U. Iraola, and M. Aizpurua, "Modular battery energy storage system design factors analysis to improve battery-pack reliability," Journal of Energy Storage, vol. 54, p. 105256, 2022.

[10] D. J. Rogers, L. J. Aslett, and M. C. Troffaes, "Modelling of modular battery systems under cell capacity variation and degradation," Applied Energy, vol. 283, p. 116360, 2021.

[11] A. Devie, G. Baure, and M. Dubarry, "Intrinsic variability in the degradation of a batch of commercial 18650 lithium-ion cells," Energies, vol. 11, no. 5, 2018.

[12] M. Doyle, T. F. Fuller, and J. Newman, "Modeling of galvanostatic charge and discharge of the lithium/polymer/insertion cell," Journal of The Electrochemical Society, vol. 140, no. 6, pp. 1526–1533, 1993.

[13] T. F. Fuller, M. Doyle, and J. Newman, "Simulation and optimization of the dual lithium ion insertion cell," Journal of The Electrochemical Society, vol. 141, no. 1, pp. 1–10, 1994.

[14] G. Plett, Battery Management Systems, Volume I: Battery Modeling. Artech House, 2015.

[15] A. Bizeray, S. Zhao, S. Duncan, and D. Howey, "Lithium-ion battery thermal-electrochemical model-based state estimation using orthogonal collocation and a modified extended kalman filter," Journal of Power Sources, vol. 296, pp. 400–412, 2015.

[16] C.-H. Chen, F. B. Planella, K. O'Regan, D. Gastol, W. D. Widanage, and E. Kendrick, "Development of experimental techniques for parameterization of multi-scale lithium-ion battery models," Journal of The Electrochemical Society, vol. 167, no. 8, p. 080534, 2020.

[17] U. I. . M. A. X. Dorronsoro, E. Garayalde, "Modular battery system's accessible energy analysis," 2022.

[18] D. Beck, P. Dechent, M. Junker, D. U. Sauer, and M. Dubarry, "Inhomogeneities and cell-to-cell variations in lithium-ion batteries, a review," Energies, vol. 14, no. 11, 2021.

[19] Y. Jiang, J. Jiang, C. Zhang, W. Zhang, Y. Gao, and Q. Guo, “Recognition of battery aging variations for lifepo4 batteries in 2nd use applications combining incremental capacity analysis and statistical approaches,” Journal of Power Sources, vol. 360, pp. 180–188, 2017.

[20] S. Lehner, T. Baumhöfer, and D. U. Sauer, “Disparity in initial and lifetime parameters of lithium-ion cells,” IET Electrical Systems in Transportation, vol. 6, no. 1, pp. 34–40, 2016.

[21] M. Dubarry, C. Pastor-Fernández, G. Baure, T. F. Yu, W. D. Widanage, and J. Marco, “Battery energy storage system modeling: Investigation of intrinsic cell-to-cell variations,” Journal of Energy Storage, vol. 23, pp. 19–28, 2019.

[22] C. Zhang, Y. Jiang, J. Jiang, G. Cheng, W. Diao, and W. Zhang, “Study on battery pack consistency evolutions and equilibrium diagnosis for serial- connected lithium-ion batteries,” Applied Energy, vol. 207, pp. 510–519, 2017.