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A Review on Electric Vehicle Hybrid Energy Storage Systems

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Abstract. With over 40% annual growth at market sales and decrease at air pollution outcome, electric vehicles prove to be the evolution of transportation. However, expected range and lithium battery limitations, considerably affect their adoption by consumers. In this article, hybrid energy storage systems consisting of lithium batteries and ultracapacitors, are presented thoroughly. In the first part of this paper, a complete review of ultracapacitors technology is introduced followed by classification concerning: Electrolyte and electrode class used, leakage current limitations and modelling for each available ultracapacitor type. Additional information is provided on the hybrid energy storage system regarding: Topologies/ converter layouts, exploitation of energy recovery and reduction of sizing, costs and weight. Finally, the need for a proper energy management system/controller with constant state of charge and temperature calculation is drawn, ensuring reliability, performance with maximum efficiency and lifetime.

Keywords: Lithium, Ultracapacitors, Hybrid, EV, Energy, Battery, Management

INTRODUCTION

Nowadays, global warming has become imminent. Pollution is increasing every day and measures are taken in every specific field like transportation. Electric vehicle adoption is the step required to reduce this problem [1]. Lithium-Ion battery pack is the dominant technology used in commercial EV's ensuring sustainability, performance and a decent range. This has caused EV's reaching an average of 40% sales increase yearly and expectations suggest that over 30% of the global share for vehicles will be electric as depicted in Fig. 1 by Deloitte [2]:

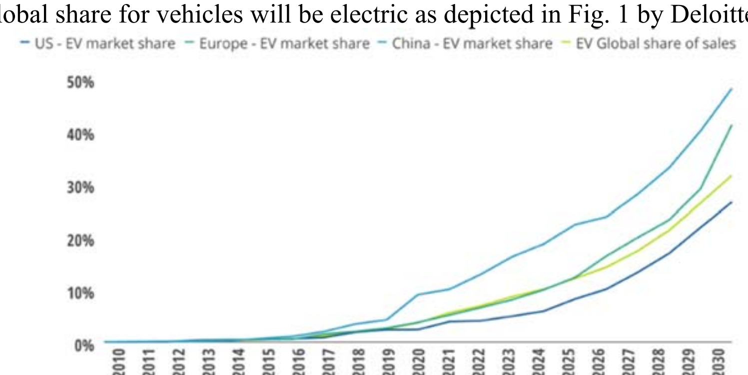

FIGURE 1. Prediction for EV market share by region[2]

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This assumption is fortuned by the margins brought via the nature of electric vehicles. Electricity is the cheapest, easy to produce and most secure - environmentally friendly energy source available [3]. However, the adoption of EV's is still bothered by certain defects [4]. These include:

- Inadequate range
- High purchase price
- Intentions of buyers
- Battery technology immaturity
- Excessive charging time

Range is a challenging factor for manufacturers. It is affected by various factors like ambient temperature [5] ,where HVAC (Heat, ventilation and Air Conditioning) is required for thermal comfort and air quality as well as battery charge balance and state of charge estimation [6-8]. Additionally, driving patterns and parameters like traffic, distance or road gradient heavily increase energy consumption [9], although low range Battery EV are preferred for quick trips due to the ability of energy regeneration, high efficiency and low cost [10]. Market conditions like customers intentions or purchase prices are criteria slowly being overcome.

The goal of this paper is an approach to examine modern hybrid energy storage systems consisting of batteries and ultracapacitors, taking in account criteria like: Technical specifications, efficiency, cost and software integration. The first one provides details on ultracapacitors and batteries technologies. In the second one, focus is centered on efficiency achieved by utilizing the hybrid system in different layouts. Energy can be regenerated greatly thus better sizing can be achieved with costs dropping adequately. In the final section, different energy management strategies are presented, combining these two energy sources to optimize power distribution. Each one of these sources has certain defects that can be eliminated with hybridization, as the results are displayed in this review.

SUPERCAPACITORS

Electrochemical capacitors, also known as ultracapacitors, are electrical components able to store certain amounts of energy in a tiny fraction of time. They consist of two electrolyte- immersed electrodes and a high-porosity separator where charge is stored by polarizing an electrolytic solution. Their development started at 1950's with first experiments conducted by General Electric (GE) with a capacity of 1 Farad. At 1982 Panasonic created their first ultracapacitor with high equivalent series resistance (ESR) and after 10 years Maxwell introduced the supercapacitor in the most recent form with low ESR and with 1KiloFarad Capacitance [11]. There are 3 main types of supercapacitors with their attributes presented at TABLE 1:

- Electric Double-Layer capacitors (EDLC)
- Pseudo or Faradaic Capacitors and
- Hybrid Supercapacitors

TABLE 1. Attributes of different supercapacitors attributes [11]

Attribute	Units	Supercapacitors			Lithium-Ion Battery
		EDLC SC	*Pseudo SC*	*Hybrid SC*	
Charge time	sec	1-10	1-10	100	600
Cycle Life	-	1,000,000	100,000	500,000	500
Cell Voltage	V	2.7	2.3 – 2.8	2.3 – 2.8	3.6
Specific Energy	W·h/kg	3-5	10	180	250
Cost per kWh	USD	8-10k	8-10k	N/A	~140
Cost per kW	USD	8-12	8-12	N/A	100-200
Op. Temperature	°C	-40 to 65	-40 to 65	-40 to 65	-20 to 60
Self-Discharge/month	%	60	60	N/A	4
Electrolyte type	-	Aprotic or protic	Protic	Aprotic	Aprotic

In EDLCs, energy storage is based on nanoscale charge divide at the interface formed by electrolyte and an electrode with no oxidation involved[12]. Because there is only physical charge transfer involved, long cycle life is ensured. At Pseudo, electrodes are based on metal oxides and conductive polymers thus achieving better energy density but very short cycle lives. On the other hand, hybrid incorporates both mechanisms from both of the last two technologies but without their disadvantages. Their schematic is portrayed at Fig. 2:

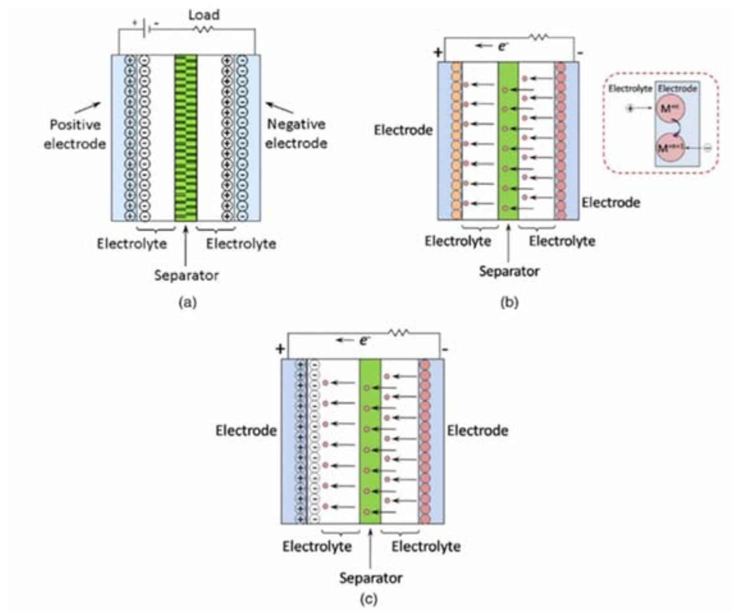

FIGURE 2. Schematic presentation of UC types: (a) EDLC, (b) pseudo and (c) Hybrid UC [12]

Further classification according to the electrolyte type is possible:

- Symmetric, using DL material for both electrodes and are the most common SC
- Asymmetric, which due to aqueous electrolyte utilization suffer from low efficiencies and lifetime
- Hybrid, the new era of SC with greater energy densities but still quite expensive

Besides hybrid ultracapacitors, the other technologies suffer from self-discharge mechanism resulted by current leakage through the ion-conductive membrane at the separator hence energy is lost [13]. But since they can endure high power handling exploiting energy recovery fast without compromising life cycle [14], ultracapacitors have become an area of intense research including:

i. Materials used for manufacturing (carbon nanotubes, graphene nanosheets) and template synthesis methods [15,16].
ii. Reliability factors and ultracapacitor mission analysis (area of usage, temperature range) for lifetime prediction [17],
iii. Charging and discharging methods; minimal energy loss and constant feed of the Ultracapacitor with minimization of current leakage due to ESR effect [18,19].

The Equivalent Series Resistance (ESR) and double layer capacitance- DLC (C_{dl}) are the two main factors affecting aging of the ultracapacitors [20,21]. If ESR is high leakage current and temperature increase thus capacitors ages faster. Typical ESR values of current UC stand in the range of 0.1 to 7mΩ [22]. On the other hand, DLC characterizes the energy storage capability of the UC and is expressed in Equation 1 as follows:

$$C_{dl} = \frac{e_S * S}{d} \qquad (1)$$

Where: ε_s displays dielectric permittivity of solvent used
S counts for contact surface between electrolyte and electrodes and
d represents the average thickness of double layer

Modelling of the ultracapacitors for further simplification of ESR value has challenged researchers around the world. From simplified model[22] to three-phase and dynamic models[23] and lastly a variable capacity model depending on various conditions[24] as depicted at Fig. 3:

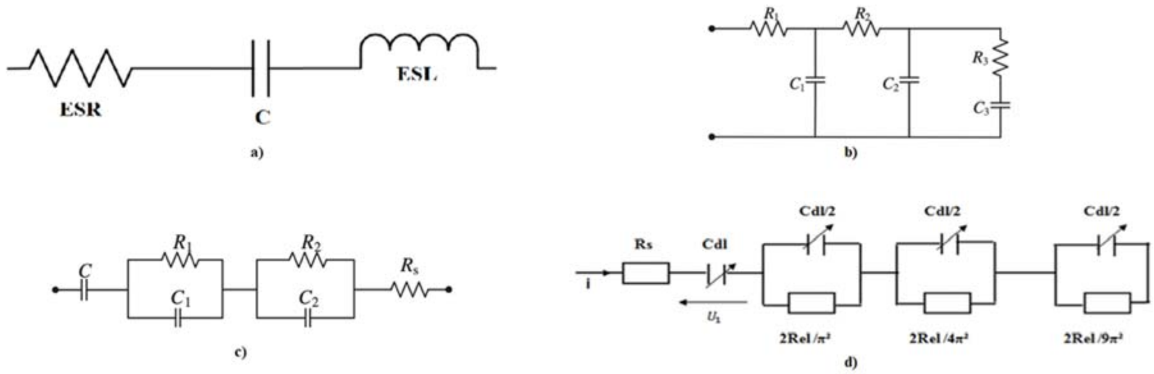

FIGURE 3. Summary of all 4 UC models by various sources: a) Simplified model, b) Three phase model, c) Dynamic model and d) Variable capacity model [22-24]

At simplified model, capacitance, series resistance and inductance are drawn although series resistance is the main factor that affects supercapacitor leakage. Thus, it is further processed and analysed at three phase and dynamic models. Variable capacity model focuses primarily on the energy and dynamic behavior of the ultrapacacitor due to voltage and capacitance changes, actively presenting the lease mean square error ensuring reliability and real representation [24].

Additional characterization of UC modelling depending on the study purpose (thermal modelling, self-discharge) are shown at Fig. 4 [25] and include:

- ◊ Electrochemical modelling, for the interior chemical design of the UC
- ◊ Fractional- order model, which is a time- domain approach with specific elements
- ◊ Intelligent model, like Neural network and fuzzy logic modelling

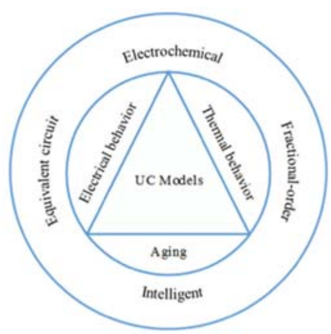

FIGURE 4. Supercapacitor modelling[25]

Therefore, calculating ESR, hence total leakage current, State of Charge and state of health is greatly important for the supercapacitors. Because these devices are used in different applications like power electronics, renewables, communication and UPS, the aging factor that is depending on these parameters has to be perfectly evaluated. Problems can be massively resolved using hybrid supercapacitors, which can be really thin and flexible26. The electrodes used may be of different material, like redox, inorganic or carbon/metal oxide electrodes to enhance capacitance along with other components like separator, current collectors and sealants being improved [27,28]. In this way, leakage current is almost eliminated while sustaining superior specific capacitance up to 500F per UC and adequate energy density which is also an issue. Lastly operation and purchase expenditure are way lower. Cycle life, energy and power densities are summarized at TABLE 2 below:

TABLE 2. Characteristics of technologies available

A/A	Technology	Characteristics		
		Cycle Life	*Energy Density*	*Power Density*
1	Lithium Battery	Low	High	Low
2	EDLC UC	High	Low	High
3	Pseudo UC	Low	Moderate	Moderate
4	Hybrid UC	High	High	Moderate-High

HYBRID ENERGY STORAGE: BATTERY AND ULTRACAPACITORS

To ensure the advantages of both technologies, merging lithium batteries and ultracapacitors is proved to be the next step. There are obvious and imminent possibilities, like heating the battery at start up so that it stays within optimal range for maximum range and minimal degradation [29]. Coverage of the Air-Conditioning system, which typically decreases EV range by 36%, can be accomplished partially by ultracapacitors in a H.E.S.S to reach desired temperature 32% faster with 16% less power losses [30].

Because ultracapacitors can handle peak currents and fluctuations to smooth power output over EV acceleration-deceleration with less heat generated [31-33] proved by Matlab modelling and DC links tests. These tests highlight the supporting role that UC can play, despite ambient temperature, vehicle size and driving cycle providing essential transient energy at different loads [34]. Therefore, battery stress is considerably reduced as battery works more efficiently at optimal conditions and range is almost 30% increased [35] while ultracapacitor capacity dropping 20% after 7 million cycles, prolonging battery life almost 2.5 times [36,37].

Sizing has also been a great focus of researchers. Randomly increasing a higher capacity ultracapacitor increases cost, weight without additional gains [38]. A study [39], suggested that using 310Wh UC over 83kWh lithium battery, that is 0.4% of the energy density, is enough to supply the additional energy and cover all peak loads without damaging the accumulator. This scheme can be also used in Hybrid electric vehicles for high frequency currents on eco or hybrid mode [40]. Hence battery lifetime can be massively enhanced, over seventy percent [41] with just 72 ultracapacitor cells, while being compact, secure and effective at each specific application42. Comparison of each individual component is presented at Fig.5 [43,44]:

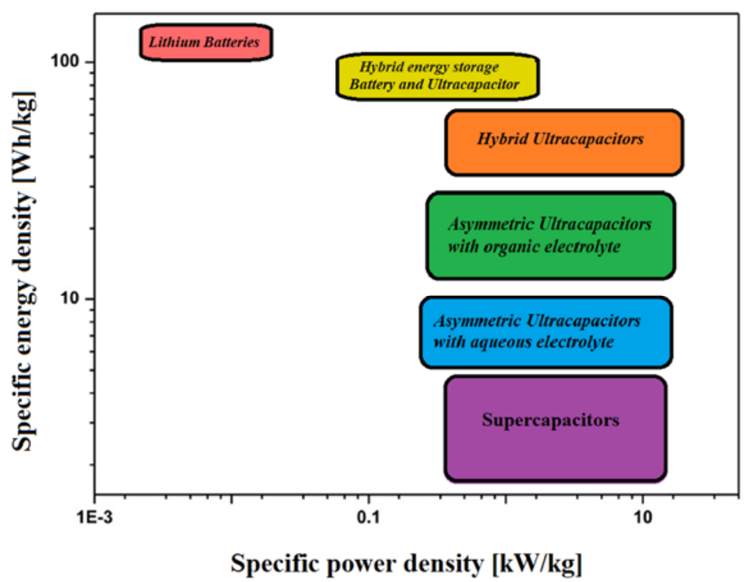

FIGURE 5. Comparison of different energy storage technologies [43,44]

The next step to be considered, is the topology configuration. Different layouts are used for hybrid energy storage system like passive, active and semi-active topologies[45]. Passive parallel without a bi-directional DC/DC converter where power distribution is based on the two components internal resistance. Thus, uncontrolled high frequency currents can harm the battery and voltage must be kept consistent. Meanwhile, utilizing fully active topology, the opportunity to control each energy source individually with better balancing but effecting cost and sizing severely. At semi active topologies one multiple input bidirectional DC-DC converter or two separate converters are installed. In this way, the ultracapacitors acts as a low pass filter handing all power fluctuations providing better sizing volume and even 7% more efficiency. Classification of different topologies are visualized at Fig.6:

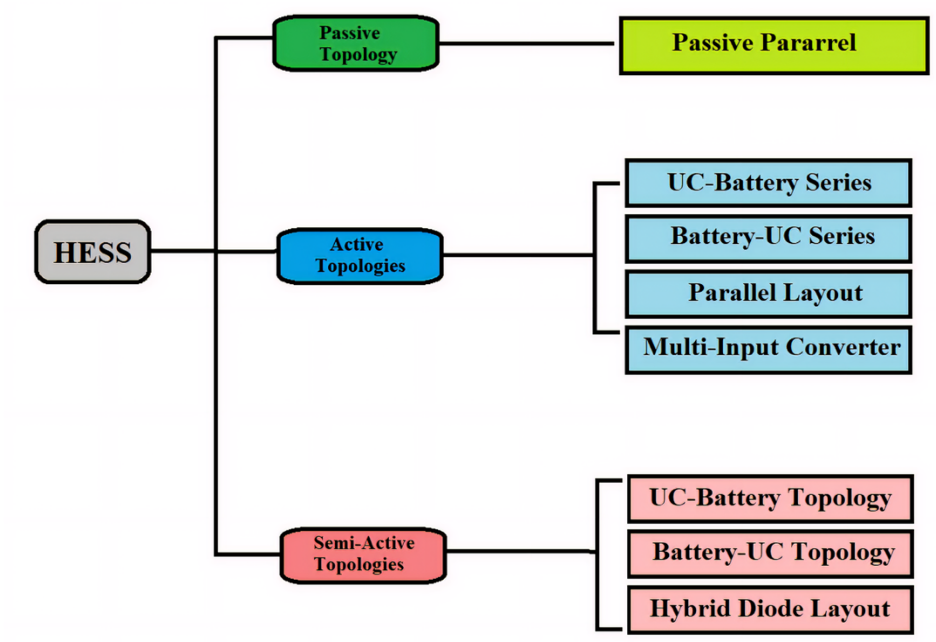

FIGURE 6. HESS topologies categorization [45]

Based on these configurations, several approaches have been followed. Employment of a Bi-Directional DC to DC converter46 directly linked to the battery and the UC is linked in series with the converter. In parallel a bypass diode is used to allow a bypass path over the converter. In that way only the battery pack is processed through the DC/DC converter with the ultracapacitor smoothing the output. On the same time the bypass diode allows the lithium battery to operate only at low power demands, ensuring higher efficiency with reduced costs. This layout is more complicated and costly than directly linking the two sources, but it does not inherit the serious drawbacks on battery life and efficiency [47]. Additionally, a different setup is proposed [48] with ultracapacitors working at higher voltage than the battery pack with the same idea: the ultracapacitors must cover all high current demands while the battery, via a diode in series, will work less at this stage and only be utilized fully at lower and more constant loads. Therefore, less heat is generated, and a smaller DC/DC converter is required hence better sizing can be performed. It can be concluded that a simple bi-directional DC/DC converter is the best solution for enhancing battery life, cost saving and weight [49]. But this oversimplified layout definitely requires a good energy management strategy, to fully balance the power output at different loads while ensuring optimal state of charge for both energy sources [50]. Accordingly, range- energy regeneration and efficiency will be maximized, at lower costs, ageing and total system weight [50,51]. A summary of HESS configurations is presented at Fig. 7:

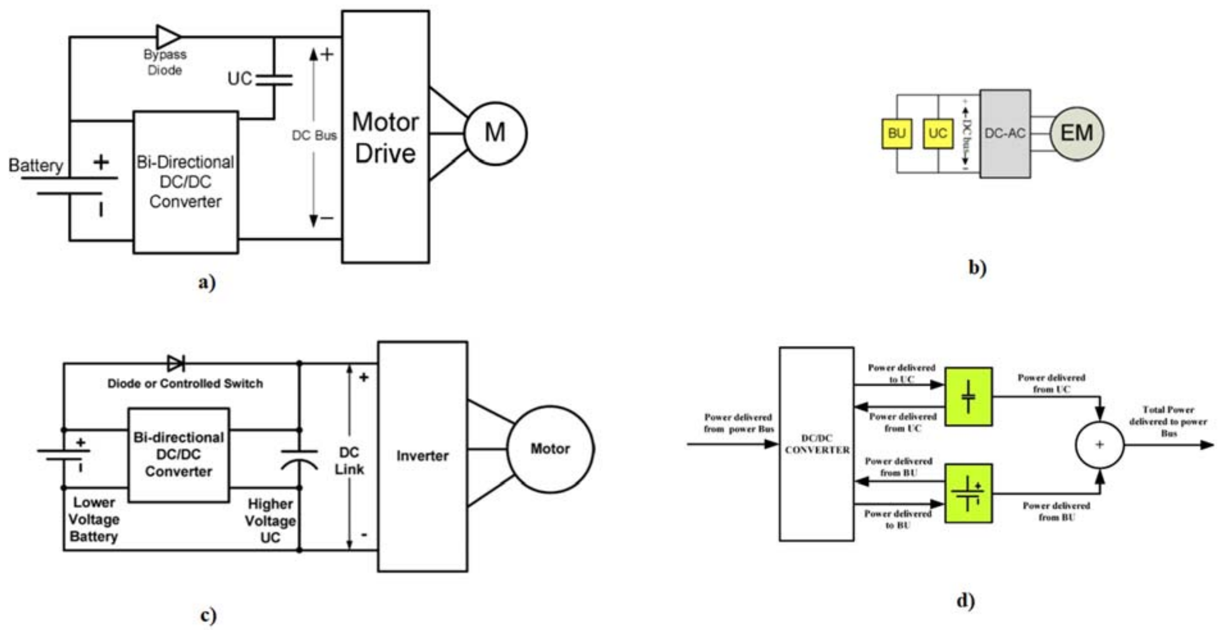

FIGURE 7. Different topologies suggested by literature: a) Bi-Directional DC to DC converter directly linked to the battery, b) Simplified HESS link with DC-AC converter, c) Bi-Directional DC to DC converter with ultracapacitors in parallel and d) Simplified Bi-Directional link [47-51]

It is also obvious that in order to achieve better management and supervision of the energy sources characteristics a proper Energy management System (EMS) is needed. This system has to predict the ultracapacitors bank capacitance at different temperatures so that constant charges and discharges provide the maximum advantage and protection for the battery pack [52,53]. Discharge cycles, followed by Peukert's law optimization, guarantee that UC will cover peak currents while fully utilizing energy recovery from regenerative breaking [54,55]. Hence:

a. Battery degradation will be limited sufficiently, with constant state of charge estimation, to prevent operation at stressful conditions like extreme temperatures [56,57],
b. Sizing can be minimized, according to Pareto Front, as less capacitors can supply the same power [58,59]
c. Costs are dropped over 20% and despite the load value [60], range can be increased up to 10%
d. Power distribution between the two sources, varies incumbent on the driving cycle, to ensure reliability, safety and performance [61].

CONCLUSIONS

The purpose of this review was to identify lithium batteries limitations and introduce supercapacitors characteristics, in order to analyze a hybrid system consisting of these two technologies. Ultracapacitors have a massive lifespan and great power density, so they can cover peak current loads and continuous charges/ discharges. Additionally, regenerative braking is fully optimized, so efficiency is raised. But because they suffer from leakage current, research has been focused on hybrid ultracapacitors and mainly at hybrid energy storage system to exploit advantages of both. Hybrid UC for example, has sufficient power and energy density but since it is a recent technology, high cost forbids their utilization. A hybrid energy storage system (HESS) uses lithium battery as the main energy source and ultracapacitors for peak currents, high loads thus battery cells protection. Preheating the battery, partly coverage of climate control needs, and excessive accelerations / decelerations are great examples of what an ultracapacitor can do. Hence, battery is excluded from applications where high temperature can harm the cells and limit lifetime by a margin. System topologies have been inspected as well as the converter configuration that manages power output and charging, for better sizing and cost reduction. It can be verified that for this layout to work, despite the assembly and installation, a complex energy management system to handle power distribution, state of charge and other calculations, is required. Depending on the charge state of both components and power needs, a modern and intelligent EMS must be able to protect the HESS from overloading and always supply sufficient energy to the motor without reaching maximum depth of discharge limits. Accordingly, range can be extended by 30% with 20% less costs and up to 2 and a half times battery life elongation.

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