Energy Storage Systems for Electric Vehicles – Indian outlook

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Abstract:- Despite the fact that Electric Vehicles are the most un-polluting vehicles because of their green nature of travel, the future of Electric Vehicle in India is uncertain. On one side, the given work provides an in-depth overview of Mechanical and, Electrochemical Storage System. And on the other hand, the work also illustrates characteristic study of variables like internal resistance, voltage, power, and thermal efficiency of battery pack generated through Simulink ADISOR, in MatLab software for batteries like Lead Acid, Nickel, Zinc-Halo, Metal-air, Lithium-ion batteries. The study also reveils characteristic features of Sodium-ion Batteries, which are the next-gen batteries. Ultimately the work reveils some unattended factors, where EV batteries require research like environment, fast charging, human safety, cost of ownership, and battery behaviour in different environmental conditions.

Keywords*: Electric Vehicle, Battery, Energy Storage Systems, Lithium-ion battery, Sodium-ion Battery, Secondary Batteries, Lead Acid Batteries, ADVISOR, MatLab, battery internal resistance, battery voltage, battery power, battery thermal efficiency*

1. Energy Storage Systems (ESSs) used in EVs - Introduction

Today, the concern of most of the governments is a clean environment, that's the reason there is a race to study a system that is non-polluting, environment-friendly and Carbon-dioxide emission-free, therefore all the countries are competing to study the storage for renewable energy and make more efficient energy storage systems (ESSs), thereby working on a smart grid system (Olivier, Peters and Janssens-Maenhout, 2012) (Omar *et al.*, 2012) (Madanipour, Montazeri-Gh and Mahmoodi-k, 2016) (Fang *et al.*, 2011; Xing *et al.*, 2011; Rahimi-Eichi *et al.*, 2013). These energy storage systems are capable of storing electrical energy, which can be used as per the requirement of the user, without much dependency on the grid for a continuous requirement of energy. And with a smart grid, we can even reverse the direction of electric energy, like during peak hours the ESSs can be used to re-energise the grid system, thereby compensating the lack of electric energy in grids or case of excessive demand of energy, and on the other side, incurring some financial incentive (or lesser price) for the end-user of ESS. Hence these energies are a result of our low dependency on fossil fuels, thereby a reduction in CO_2 (Tie and Tan, 2013).

2. ESSs & their classification

ESSs are classified based on chemical, thermal, mechanical, electro-mechanical and hybrid systems, based on conversion and utilization of energy. Further, these are categorized based on fabrication and material used (Lv *et al.*, 2015).

A. Mechanical Storage Systems (MSS)

MSSs are the oldest and most conventional energy storage systems. Attributing to its low initial cost, easy installation, and cheap maintenance cost. These include Flywheel Energy Storage (FES), and Compressed Air Energy Storage (CAES), and the most common and oldest Pumped Hydro Storage (PHS) which is used to generate electricity in hydro-power plants or pumped hydro storage, contributing to almost more than 99 per cent of electricity stored worldwide, and almost 4% of electricity generated worldwide. In this system, stored water with high pressure is used to rotate a turbine that is meshed with an electric power generator. On the other side, electricity is also produced in a turbine by the method of Compressed Air Energy Storage system, in which compressed air is added to clean air, and then pressurized, and compressed again, and finally fed to the turbine, that generates electricity on meshing with an electrical generator (Dhameja, 2001).

On the other hand, research in material engineering has led to another phenomenon called Flywheel Energy Storage Systems (Vazquez *et al.*, 2010). These storage systems are much more efficient with an efficiency rating of 90% (Lemofouet and Rufer, 2006; Bolund, Bernhoff and Leijon, 2007; Liu and Jiang, 2007; Vazquez *et al.*, 2010; van Berkel *et al.*, 2014; K. Xu *et al.*, 2016; Y. Xu *et al.*, 2016). To produce electricity from a flywheel, first of all, a cylindrical block is placed over a shaft with bearings, and then further connected with a power generation device. With the rotation of this cylindrical block, also called a flywheel, the power generator generates electricity (Vazquez *et al.*, 2010; Fang *et al.*, 2011; Han and Xu, 2011). The energy extracted from the flywheel is given by:

$E_K = 1 / (2I\omega^2)$,

where,

E_K = Kinetic Energy developed in the flywheel

I = Moment of Inertia (of the cylinder)

ω = speed of the flywheel

(Bolund, Bernhoff and Leijon, 2007)

Here, the kinetic energy developed in the flywheel is inversely proportional to the rotational speed as well as the square of the moment of inertia, so this energy can be increased exponentially, by decreasing either the speed of the flywheel or the moment of inertia. Despite high losses that incur in flywheel energy storage, which even makes it a self-discharging storage system, there are some advantages of this system like low initial cost, infinite charge storage, long life, high power density, high energy storage, less depth of discharge, etc (Lemofouet and Rufer, 2006; Liu and Jiang, 2007; Vazquez *et al.*, 2010). This disadvantage of self-discharging can be overcome by utilizing no-friction bearings (Lemofouet and Rufer, 2006; Liu and Jiang, 2007; Vazquez *et al.*, 2010). This is a mechanical system that is never used alone, but always in integration with other storage systems (Bolund, Bernhoff and Leijon, 2007; van Berkel *et al.*, 2014; K. Xu *et al.*, 2016; Y. Xu *et al.*, 2016).

B. Electrochemical Storage Systems (EcSS)

A system in which we store electric charge in the form of the chemical is called Electrochemical Storage Systems. It comprises of all rechargeable and non-rechargable betteries (Ogata *et al.*, 2016). Since electric vehicle comprises rechargeable batteries, in this work we have only discussed rechargeable batteries. In EcSSs, first, we convert electric energy to chemical energy using some chemical reactions to store charge, and then to extract this stored charge, we again extract this electric charge from chemical by some chemical reactions (Hiroshima *et al.*, 2016). This even shortens the life of the battery to some extent, but the charge and discharge are not only environment friendly, but also emission-less and maintenance-free (Ibrahim, Ilinca and Perron, 2008; Yuan, Sun and Huang, 2016). EcSSs are of two types, namely Flow Batteries, and Secondary rechargeable batteries.

C. Flow Batteries (FB)

Flow Batteries constitute electro-active species, which stores energy. They are mainly rechargeable in nature. In this system, electro-active species, which is mixed with the electrolyte is pumped through an electro-chemical cell, so that chemical energy can be converted to electric energy. Redox Flow Batteries are very efficient and flexible in terms of power and cycle stability(Yuan, Sun and Huang, 2016).

D. Secondary Storage Batteries (SSBs)

Secondary Storage is a form of rechargeable battery and is prominent in the Electric Vehicle industry for the storage of electric charge. Secondary storage batteries also utilize electrochemical reactions in case of storage of time and at the time of extraction of charge for utility. Different types of secondary storage batteries used in electric vehicles mainly include Lead Acid batteries, Ni-based batteries like (Nickel-Ferrous, Nickel-Zinc, Nickel-Cadmium, Nickel-Hydrogen), Zinc-Halo batteries (like Zinc-Chloride, Zinc-Bromide), N—Beta (like Sodium-Sulfur), Metal-air base batteries (like Ferrous-air, Aluminium-Air, Zinc-air). Lithium batteries are further divided into high-temperature Lithium (Lithium-Al-FeS, Lithium-Al-FeS_2) and ambient temperature Lithium (Li-polymer, Li-ion) batteries. To construct, it requires only two charged electrodes (namely anode and cathode), separated by a separator in a case, filled with an electrolyte (Fang *et al.*, 2011; Lu *et al.*, 2013) (Ren, Ma and Cong, 2015). These batteries are considered for EVs because of their high-power density and specific energy, negligible resistance and memory effect, and thermal independence (Lu *et al.*, 2013). But considering the nature of electrolytes and the electrochemical process happening inside the batteries, these batteries are harmful to the environment (Yin *et al.*, 2013).

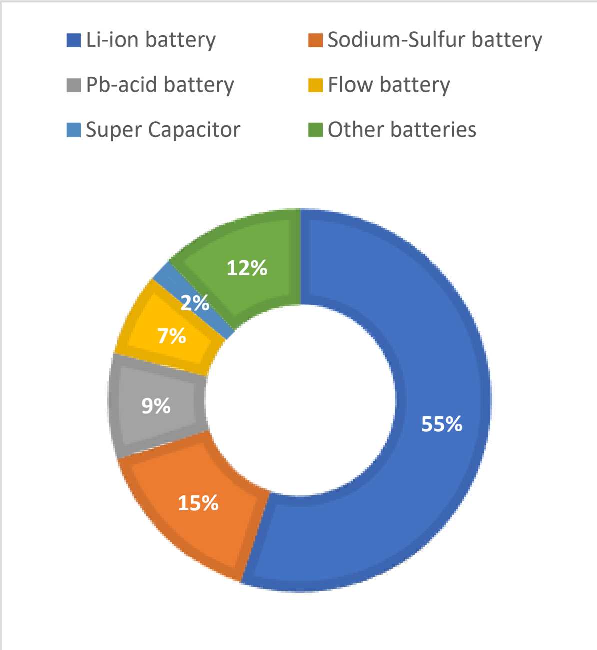


Figure 1 Rechargeable secondary storage batteries were used in the year 2016 worldwide (Zhang *et al.*, 2018)

3. Secondary Storage Batteries (SSBs) for EV application

A. Lead Acid Batteries

In India, the battery produced is the inferior quality (with an energy density of 30 $Whkg^{-1}$) as compared to the ones used in other countries (with energy density ~40 $Whkg^{-1}$), therefore the battery is not suitable for use in electric vehicles, but these are intensively used to electrify IC Engine cars (Sivaramaiah and Subramanian, 1992). These batteries have high thermal tolerance, low initial cost and maintenance cost (Lukic *et al.*, 2008; Atwater and Dobley, 2011). Attributing to their harmful effects while recycling, in India, there are several methods, through which these batteries are recycled in India like Pyro-metallurgy, Hydro-metallurgy, etc (Varshney *et al.*, 2019).

Construction: In this, we place lead as a negative anode, lead oxide in the place of positive cathode and Sulfuric Acid as electrolyte reacting as under:

$$Pb + 2PbO_2 + 2H_2SO4 \rightleftharpoons 2PbSO_4 + 2H_2O$$

Working: As per the provided equation, $PbSO_4$ is extracted during discharge along, and on the other hand water is produced during charging (Chau, Wong and Chan, 1999).

B. Nickel batteries

These batteries are a little more expensive than Lead Acid batteries. Considering factors like high initial cost and maintenance cost, low power and life cycle, these Nickel batteries are discouraged for use in electric vehicles(Chau, Wong and Chan, 1999). For example, considering the number of life cycles of Ni-Cadmium, which is more than 2000, and high energy density, the cost of Nickel battery is about ten times that of lead-acid (Chau, Wong and Chan, 1999; Divya and Østergaard, 2009; Khaligh and Li, 2010; Zhou *et al.*, 2013; García-Plaza *et al.*, 2015; Li *et al.*, 2016) (Hadjipaschalis, Poullikkas and Efthimiou, 2009). On the other hand, Ni-Hydrogen battery has a high life cycle, resistance to over and dis-charge, and high capacity, but is very costly, has a self dis-charge and a very low volumetric energy potential (Atwater and Dobley, 2011; Li *et al.*, 2016). For the abovesaid reasons, these Nickel batteries are discourages in India, even for IC Engines.

Construction: These batteries comprise Ni-hydroxide in the place of the cathode, along with a corresponding anode.

Working: Anode decides the type of battery, like Ni-Ferrous battery, Ni-Cadmium battery, Ni-Zinc battery, and Ni-Hydrogen battery (Chau, Wong and Chan, 1999; Atwater and Dobley, 2011; Tie and Tan, 2013; Li *et al.*, 2016). The reaction taking place in a Ni-based battery is as follows:

$X + 2NiO(OH) + 2H_2O \rightleftharpoons 2Ni(OH)_2 + X(OH)_2$; where X = Fe/Cd/Zn

$(M)H + 2NiO(OH) \rightleftharpoons M + Ni(OH)_2$

$H_2 + NiO(OH) \rightleftharpoons Ni(OH)_2$

C. Zinc-Halo Batteries

These batteries were developed in the late 1970s for static charge storage as Zinc-Bromide and Zinc-Chloride (Lv *et al.*, 2015). Of these two, Zinc-Bromide is used in the electric vehicle because of its fast-charge properties, high specific energy of 70 Wh/kg, and the less initial cost of material and manufacturing (Chau, Wong and Chan, 1999; Manla *et al.*, 2009; Atwater and Dobley, 2011; Lai *et al.*, 2013). Zinc-Halo batteries are not used in India attributing to user analytics, which showed discontentment in terms of its low specific power which is 90W/kg, the requirement of the large case for electrolytic reaction, thermal instability, and high reactivity of Bromine, and it was discouraged for use worldwide (Chau, Wong and Chan, 1999; Atwater and Dobley, 2011; Lai *et al.*, 2013). Construction: $ZnBr_2$ battery tank consists of zinc and bromine as two electrodes, along with Zinc-Bromide solution aqueous solution as an electrolyte.

Working: During the process of charging, Zinc and Bromine need to be pumped to these electrodes, which in turn deposits Br_2 on the positive electrode and Zn on the negative electrode, and vice versa in case of discharging (Chau, Wong and Chan, 1999; Atwater and Dobley, 2011). The reactions are given as under:

$ZnBr_2(aq) \rightleftharpoons Zn\ 0 + Br(aq)$

D. Metal-air-electro-chemical batteries

Construction: These batteries have a metal anode and an oxygen cathode on the other side (Atwater and Dobley, 2011; Lee *et al.*, 2011; Cheng and Chen, 2012; Wang *et al.*, 2014; Zhang *et al.*, 2016). Further, we use Calcium, Magnesium, Lithium Iron Phosphate (LFP), Aluminium and Zinc as the anode (Atwater and Dobley, 2011; Lee *et al.*, 2011; Cheng and Chen, 2012; Wang *et al.*, 2014; Zhang *et al.*, 2016).

Of these, experiments show that Lithium-air battery exhibits the maximum specific energy of 11.12 kWh/kg, in absence of air, that is almost a hundred times, that of the others, which makes it the most prominent battery to be used in electric vehicle applications (Lee *et al.*, 2011; Gallagher *et al.*, 2014; Ma *et al.*, 2015; Lim *et al.*, 2016; Yang *et al.*, 2016). But Lithium-air battery is highly susceptible to fire as it readily combines with humidity in the air.

Calcium – Air is very costly in comparison with others, but on a positive note, has better energy density. To ensure high efficiency, this Calcium is always used as an alloy (Wang *et al.*, 2014).

Aluminium – Air has a better ampere-hour capacity, with a high terminal voltage and specific energy. But the biggest disadvantage in this battery is the consumption of water during discharging (Atwater and Dobley, 2011; Wang *et al.*, 2014). The maintenance of these batteries requires Aluminium anode replacement after each discharge (Atwater and Dobley, 2011). To make this even more efficient, Aluminium is used in Alloy form to attain 98% electric charge efficiency (Zhao *et al.*, 2015). Such a battery is often used in underwater vehicles. It is also pertinent to mention that Aluminium-Oxygen battery is a commonly used in e-vehicles, as Al and O2 combine to produce double the energy per kilogram that of oxygen and hydrogen – FC (Atwater and Dobley, 2011; Lee *et al.*, 2011; Cheng and Chen, 2012; Wang *et al.*, 2014; Zhang *et al.*, 2016).

Zn-Air battery is a very efficient battery in terms of mechanical and electric rechargeability. The formation and charging of Zn-air batteries depend upon varying airflow (Sapkota and Kim, 2009; Atwater and Dobley, 2011; Lee *et al.*, 2011; Li *et al.*, 2013; Wang *et al.*, 2014).

Advantages: The advantages of these batteries include high specific energy and low initial cost, for which it is also considered favourable for eV applications (Atwater and Dobley, 2011; Spanos, Turney and Fthenakis, 2015).

Construction: In this battery, there are two electrodes namely the Xn electrode and the Air electrode.

Working: During discharge, the Zn electrode oxidizes on losing/ releasing electrons, whereas, on the other side, the air electrode produces Hydroxyl ions. And ultimately, during charging, Zn deposits on the Zn electrode, and oxygen is dissipated into the air (Akhil *et al.*, 2013). The overall equation is given as follows:

$$4Me + nO_2 + 2nH_2O \rightleftharpoons 4Me(OH)_n$$

Where:	Me	=	Metal like Lithium, Calcium, Iron, Aluminium, Zinc
	n	=	no of molecules according to valence

E. Li-ion batteries

Super-lightweight along with high energy density, high power and high specific energy, no memory effect and unharmful behaviour for the environment are the factors that make Lithium batteries the most widely used batteries for EV application (Akhil *et al.*, 2013; Tie and Tan, 2013). But it is noteworthy that the Li-batteries are the most expensive batteries in the segment. Otherwise, these batteries require cell balancing systems for better performance (Tie and Tan, 2013; Zhou *et al.*, 2013; Hoque, Hannan and Mohamed, 2016; Sun, Liu and Cui, 2016).

Lithium-Sulphide batteries amongst Lithium-battery storage systems can sustain as high temperatures as 375-500 degrees Celsius(Lv *et al.*, 2015) (Atwater and Dobley, 2011). Some batteries like LiAl-FeS (Lithium Aluminium Iron-Sulphide) and LiAl-FeS2 (Lithium Aluminium Iron-Disulphide) can sustain very high temperatures (Lv *et al.*, 2015) (Dincer and Rosen, 2002; Atwater and Dobley, 2011). These are the lightest ones with the highest capacity among the Li-battery segment. But the disadvantages include – low life cycles, and the requirement of a thermal balancing system (Tie and Tan, 2013; Lv *et al.*, 2015). Since these batteries are used in EV's, which use electronic motors rather than Fossil-fuel engines, therefore, the initial weight of the vehicle reduces, and further the associated losses or resistances like tyre-rolling, aerodynamic drag, etc. (Masias, Marcicki and Paxton, 2021)

Construction - These batteries include anode as Lithium-Aluminium alloy (used to oversee Lithium activity), whereas cathode includes Iron-Sulphide (to prevent corrosion of Iron), and on the other hand, the electrolyte used is Lithium-Chloride -Potassium-Chloride, with a separator (Dincer and Rosen, 2002) (Lv *et al.*, 2015). The overall reaction in this battery is as given below:

$$2\,Li - AlFeS \rightleftharpoons 2Al + Fe + Li2_S$$

$2Li - Al + FeS_2 \rightleftharpoons 2Al + Fe + Li_2FeS_2$

The main commonl used Lithium batteries for EV applications are Lithium-poly and Lithium-ion batteries, which operate at mediocre temperatures (Cotterman, 2013) (Lv *et al.*, 2015). Amongst the two, Lithium-poly batteries use Li-metal as one of their constituents, but Lithium-ion does not utilise Li-metal (Lv *et al.*, 2015). Lithium-polymer batteries are tough and therefore, are used for packaging to a variety of shapes, and have poor density, low conductivity, high specific energy of 155 W-h/kg and power need of 315 W/kg (Akhil *et al.*, 2013; Tie and Tan, 2013; Zhou *et al.*, 2013; ECOFYS, 2014; Capasso and Veneri, 2015; Zheng *et al.*, 2015; Rashid, 2017). On the other side, Lithium-ion was proposed by Bell Labs in the late 1960s and later on taken up by Sony Industries for commercial production attributing to its high power density in the range 500 – 2000 W/kg, lightweight, small size, high energy density (Akhil *et al.*, 2013; Zhou *et al.*, 2013; ECOFYS, 2014; Capasso and Veneri, 2015; Zheng *et al.*, 2015; Li *et al.*, 2016) (Hadjipaschalis, Poullikkas and Efthimiou, 2009). But deep discharges can affect the life cycles of these batteries, by directly impacting their temperature (Zhou *et al.*, 2013).

Li-ion batteries are further divided into Li-Cobalt Oxide ($LiCoO_2$), Li-Nickel-Manganese-cobalt (Li- NMC) oxide ($LiNiMnCoO_2$), Li-Manganese oxide ($LiMn2O_4$), Li-Nickel cobalt aluminium oxide ($LiNiCoAlO_2$), Li-Iron phosphate (LFP) ($LiFePO_4$), and Li-titanate (Li_4Ti5O1_2) batteries (Capasso and Veneri, 2015) (Lv *et al.*, 2015) according to the positive electrode. Of these, Li-titanate (Li_4Ti5O1_2) batteries support the fastest charging and are therefore used intensively for EV's (Tie and Tan, 2013).

Construction – The most recent researches say, that when we introduce oxygen-containing Lithium=functional groups through the plasma method, the performance of \Lithium-batteries improves (Zhang *et al.*, 2021). For the anode, Carbon is used in the form of Lithiated graphite; for electrolyte, Li-salts dissolved in (organic) carbonates; and Li-metal Oxide ($LiMeO_2$, like $LiMn2O_4$, $LiCoO_2$, $LiNiMnCoO_2$,$LiFePO_4$, $Li_4Ti_5O_{12}$,) and $LiNiCoAlO_2$), along with a separator. (Khaligh and Li, 2010; Atwater and Dobley, 2011; Cotterman, 2013; Zhang *et al.*, 2014; Kim *et al.*, 2015; Yu *et al.*, 2015). The equation is as given below (Chan and Chau, 2001) :

$LiMeO_2 + C \rightleftharpoons Li_{1-x} MeO_2 + Li_x C$

Working: During charging, Li-positive ion moves from cathode to anode, and integrates an electron, thereby getting accumulated in between carbon layers. And while discharging, this whole process reverses and an ion is formed again (Duvall and Alexander, 2005; Chen *et al.*, 2009; Khaligh and Li, 2010; Zhang *et al.*, 2014; Kim *et al.*, 2015). But this process out-dates to 1991, when Sony was manufacturing Li-batteries, so more technologies are under research for utilization in EV's, as they require high-pace and high energy batteries (Duvall and Alexander, 2005; Nazri and Pistoia, 2008; Khaligh and Li, 2010; Akhil *et al.*, 2013; Lee *et al.*, 2016).

4. Comparative study of Lead Acid, Nickel, Zinc Halo, Metal-air, and Lithium-ion Batteries

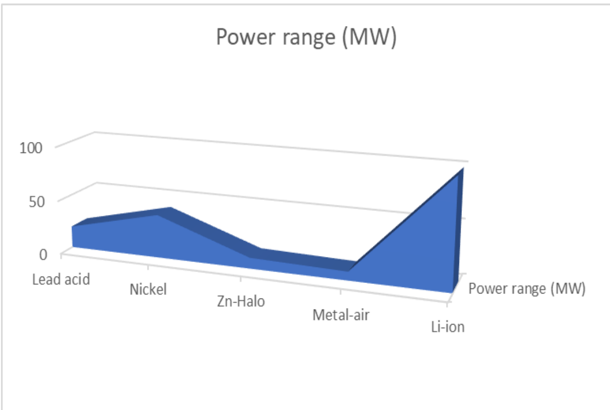


Figure 2 Comparison of different batteries in terms of Power Range (Akinyele and Rayudu, 2014; Nadeem *et al.*, 2018; Krishan and Suhag, 2019)

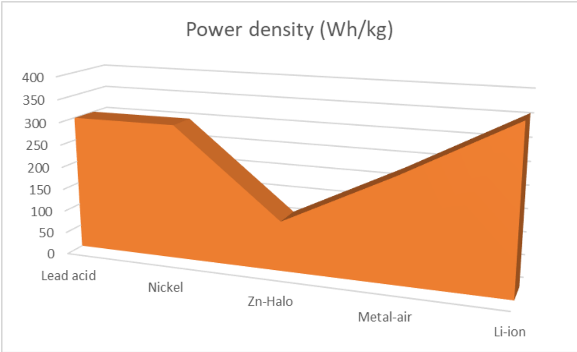


Figure 3 Comparison of different batteries in terms of Power Density (Akinyele and Rayudu, 2014; Nadeem *et al.*, 2018; Krishan and Suhag, 2019)

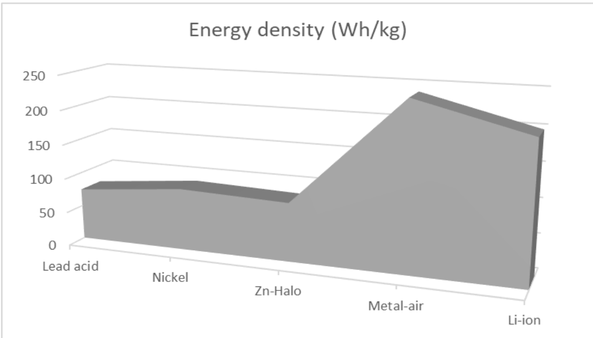


Figure 4 Comparison of different batteries in terms of Energy density (Akinyele and Rayudu, 2014; Nadeem *et al.*, 2018; Krishan and Suhag, 2019)

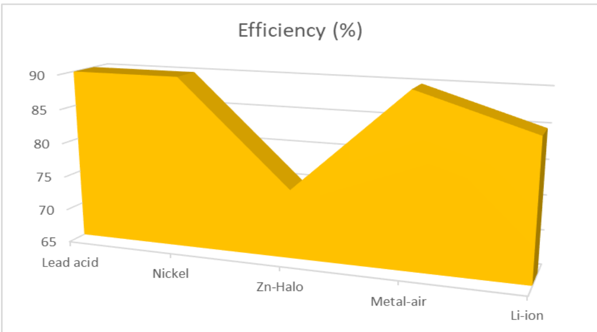


Figure 5 Comparison of different batteries in terms of Efficiency (Akinyele and Rayudu, 2014; Nadeem *et al.*, 2018; Krishan and Suhag, 2019)

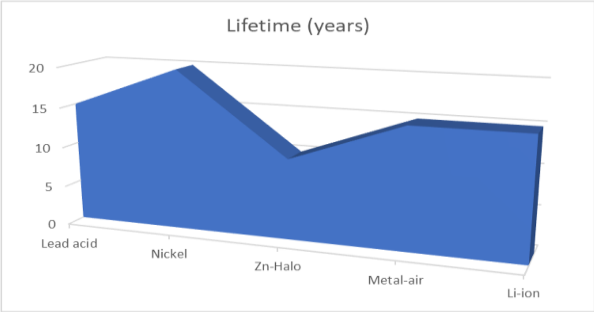


Figure 6 Comparison of different batteries in terms of Battery Life (Akinyele and Rayudu, 2014; Nadeem *et al.*, 2018; Krishan and Suhag, 2019)

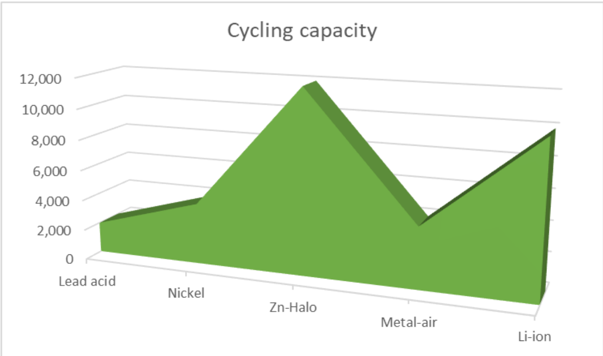


Figure 7 Comparison of different batteries in terms of recharge cycles (Akinyele and Rayudu, 2014; Nadeem *et al.*, 2018; Krishan and Suhag, 2019)

5. Accepted Standards

A simulation analysis has been performed on a virtual test vehicle keeping the characteristics/ specifications as mentioned in Table 2:

Table I. Assumed specifications of Electric Vehicle

S.No.	Description	Value
1	Weight	1400 Kg
2	Aerodynamic Frontal Area	2.91m2
3	Drag coefficient Cd	0.18
4	Constant Overhead power	143 W
5	Wheel rolling radius	0.2m
6	Wheel base	0.0024m
7	Rolling coefficient Cr	0.015
9	Battery Pack Voltage	320 V
10	Cell capacity	94.375 Ah
11	Motor max torque	275Nm
12	Peak Output	129 PS
13	Wheel radius	16 inches

6. Performance Analysis

The algorithm depicted in Figure 8 has been used to build up a battery and to perform simulation of the aforementioned battery configurations. In this algorithm, we need to enter the value of Power and its variations and the algorithm will output the maximum power of the battery pack, its maximum charging power, state of charge, and different battery temperatures.

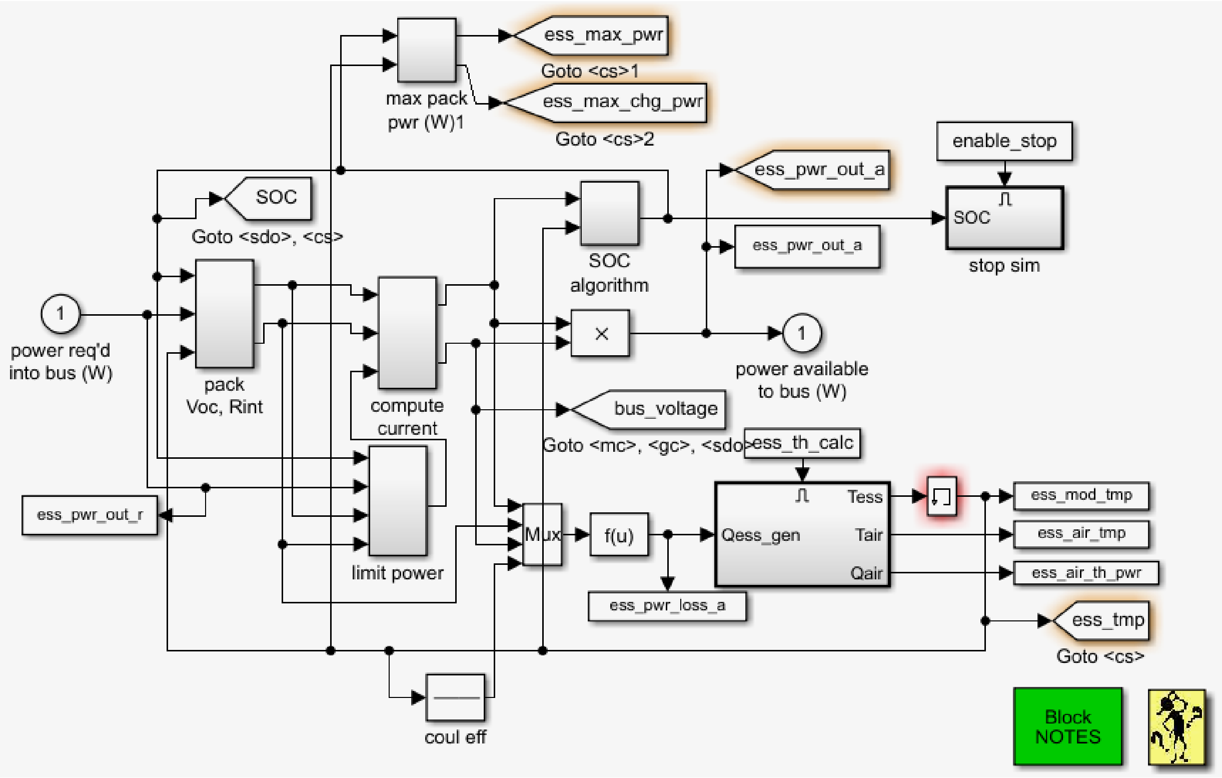


Figure 8 ESS (Battery Pack) Algorithm (MatLab Simulink ADVISOR)

With this battery algorithm, parameters like Battery Resistance, Open Circuit Voltage, Instantaneous Power, Isothermal Round-trip Efficiency (at 22 degree Celsius) of Lead Acid Battery, Lithium-ion Battery, Nickel-Metal-Hydride Battery, Nickel Cadmium Battery and Nickel-Zinc Battery have been analyzed using Matlab.

A. Battery Internal Resistance (R_{int})

Figure 9 shows algorithm to determine the Resistance with SoC approaching from 0 to 1 in a Battery Pack, as designed in MatLab.

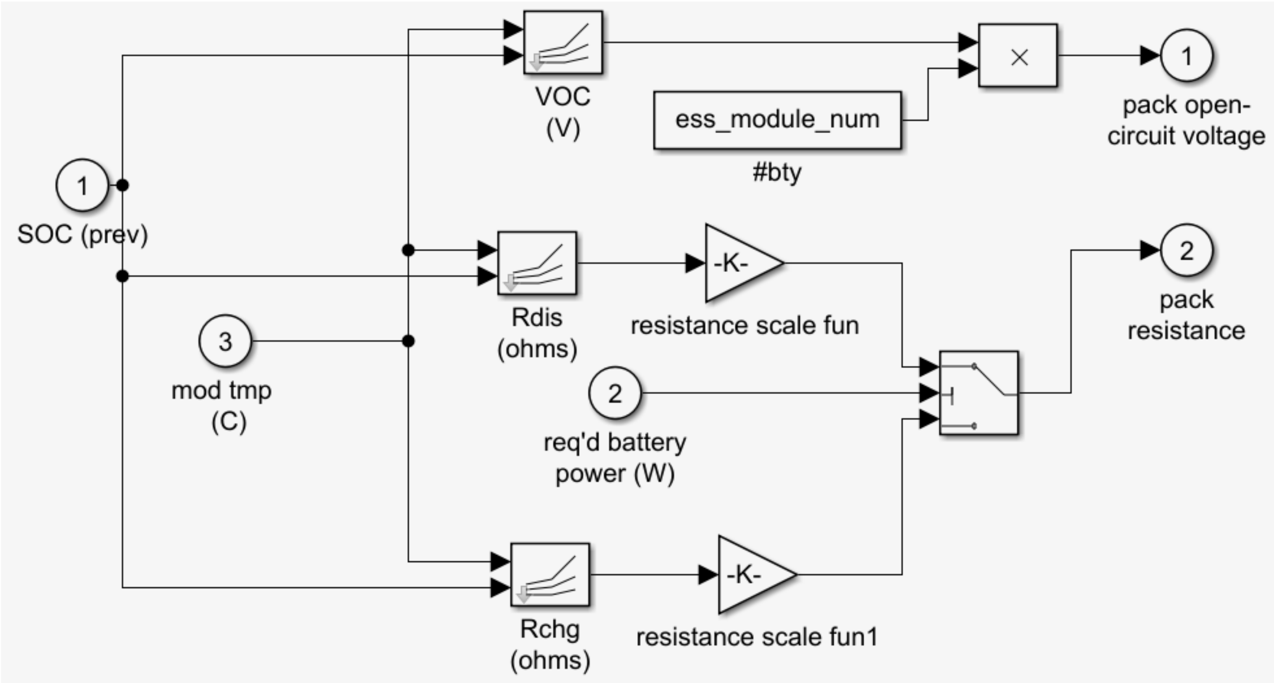


Figure 9 Algorithm for determining Battery Pack Resistance (MatLab Simulink ADVISOR)

As the State of Charge depletes in a battery with running of the eV, the battery resistance also varies. A fully depleted battery has a low state of charge, thus in order to drive the charging process and overcome the resistance inside the battery, a greater charging voltage is required.

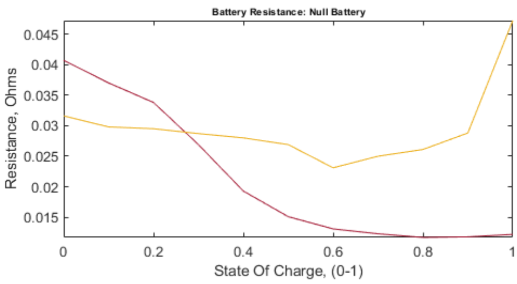


Figure 9(a) Lead-acid Battery

Figure 9(a) shows that during charging, that is SoC approaching to 1, the temperature of battery is first almost constant and then rises to maximum, with a fall in Internal Resistance, approaching Zero.

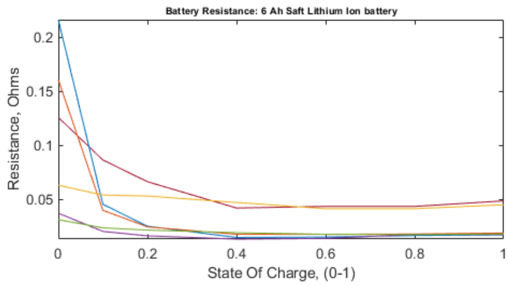
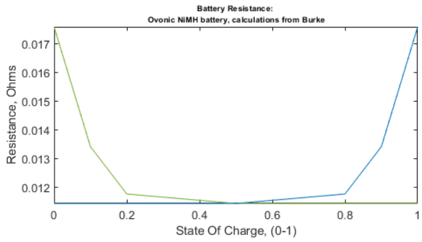


Figure 9(b) Li-ion Battery

Figure 9(b) shows that during charging, that is with SoC approaching to 1, the temperature of battery gradually decreases, with a fall in Internal Resistance, which is minimum, but not Zero.



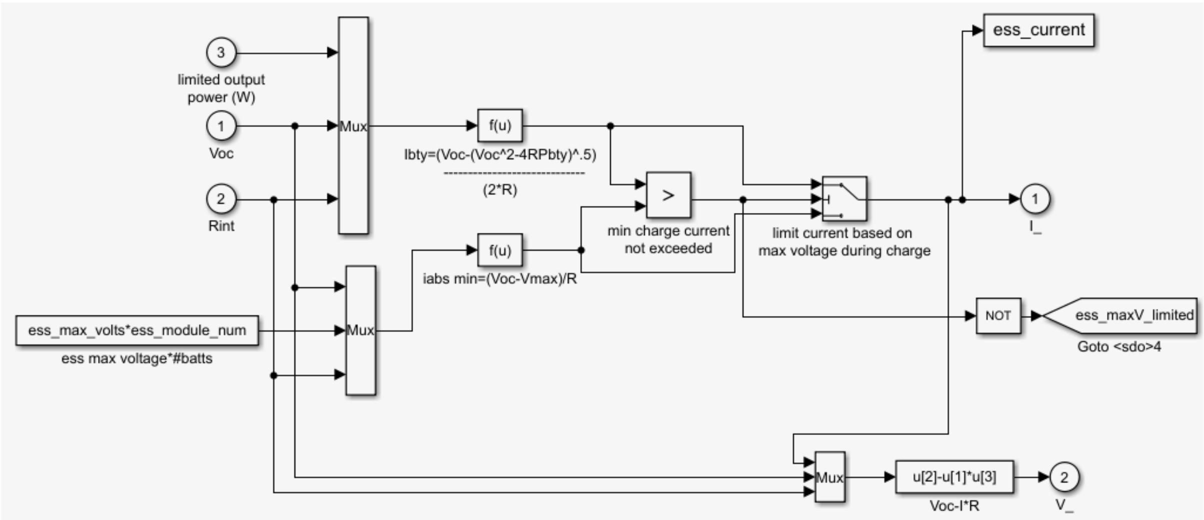


Figure 10 Algorithm for determining Battery Pack Voltage (MatLab Simulink ADVISOR)

Figure 9(c) NiMH Battery

Figure 9(c) shows that during charging, that is SoC approaching to 1, the temperature of battery rises, with a fall in Internal Resistance, approaching Zero.

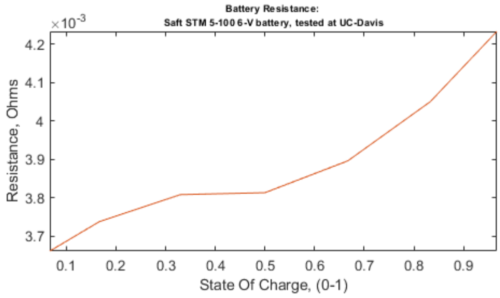


Figure 9(d) NiCd Battery

Figure 9(d) shows that during charging, that is SoC approaching to 1, the temperature of battery is coincident with the Internal Resistance.

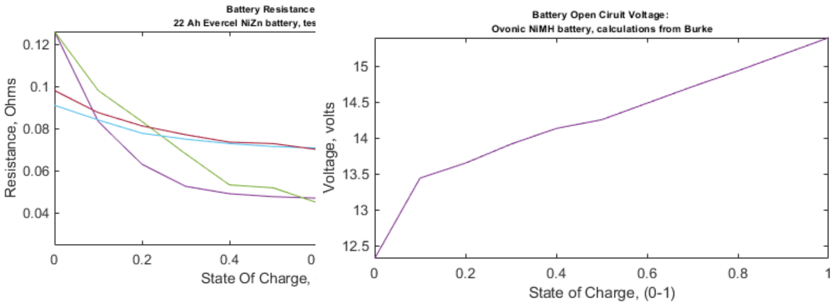


Figure 9(e) NiZn Battery

Figure 9(e) shows that during charging, that is SoC approaching to 1, the temperature of battery goes down, with a fall in Internal Resistance, typically approaching Zero.

This implies that the Ohmic Resistance inside a battery is independent of temperature.

B. Battery Voltage

Fig. 10 shows algorithm to determine the Voltage with SoC approaching from 0 to 1 in Battery Pack, as designed in MatLab.

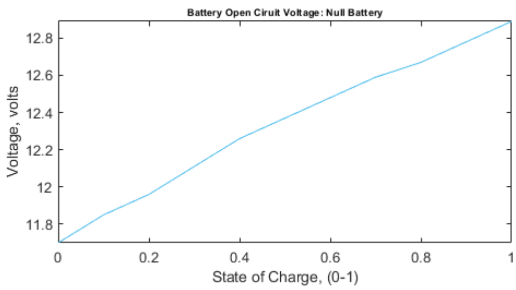


Figure 10(a) Lead Acid Battery

Figure 10(a) shows that with SoC approaching to 1, the Voltage rises in direct proportionality.

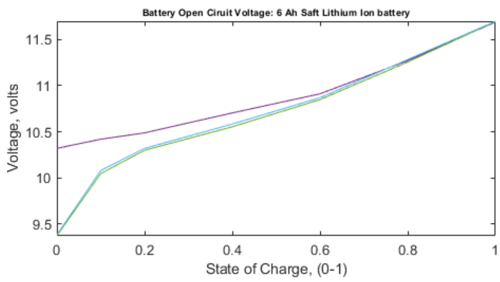


Figure 10(b) Li-ion Battery

Figure 10(b) shows that with SoC approaching to 1, the Voltage first rises exponentially to an extent and then rises in direct proportionality.

Figure 10(c) NiMH Battery

Figure 10(c) shows that with SoC approaching to 1, the Voltage first rises exponentially to an extent and then rises in direct proportionality.

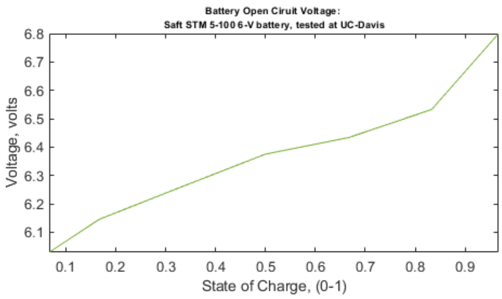


Figure 10(d) NiCd Battery

Figure 10(d) shows that with SoC approaching to 1, the Voltage first rises in direct proportionality to an extent and then rises exponentially.

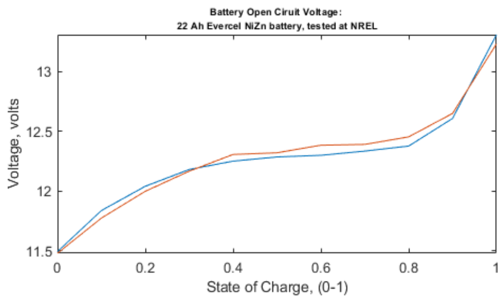


Figure 10(e) NiZn Battery

Figure 10(e**)** shows that with SoC approaching to 1, the Voltage first rises in direct proportionality to an extent and then rises exponentially.

Considering fig 10(a) to 10(e), we can conclude that for all eV batteries, the SoC & Voltage rise in direct proportionality.

C. Power

Fig. 10 shows algorithm to determine the attitude of Power with SoC approaching from 0 to 1 in a Battery Pack, as designed in MatLab.

Fig.11 represents an algorithm in which the State of Charge is fed to the system, and the system generates the maximum charging power.

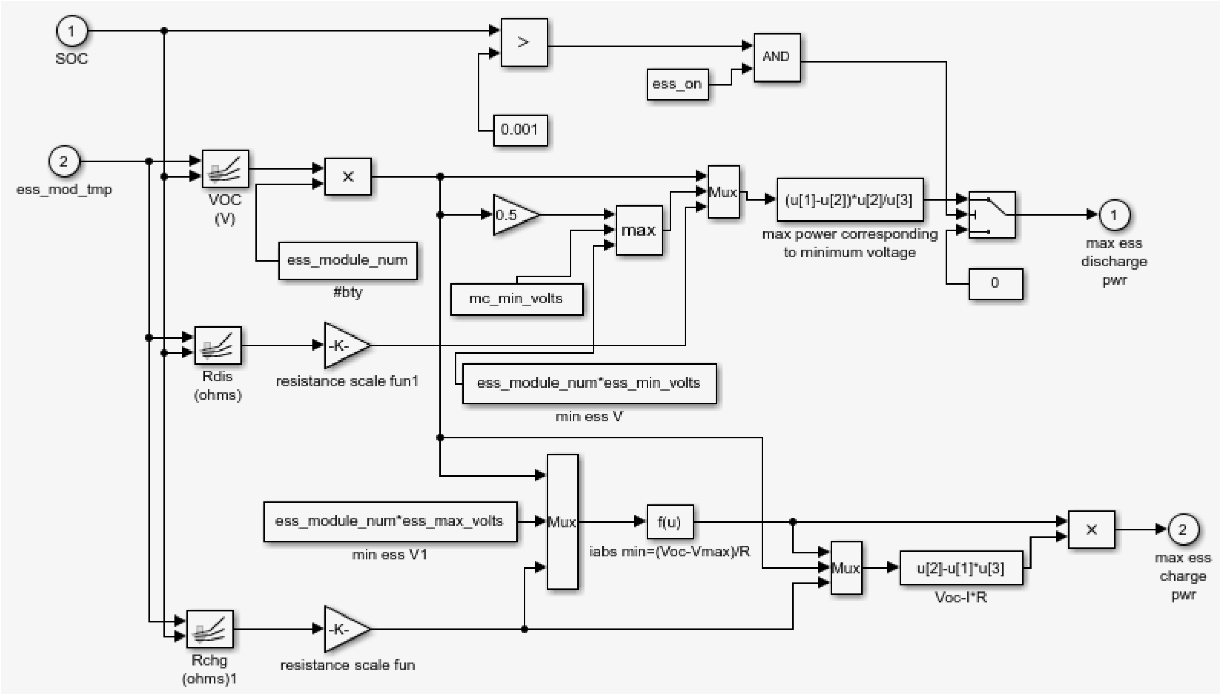


Figure 11 Algorithm for determining Battery Pack Power (MatLab Simulink ADVISOR)

Figure 11**(a) shows that with SoC approaching to 1, the Power first rises gradually to an extent, then in direct proportionality and further slows down rising.**

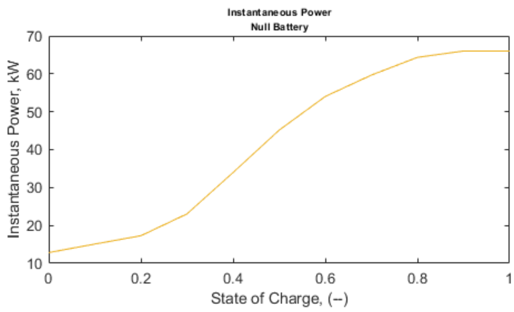


Figure 11(a) Lead Acid Battery

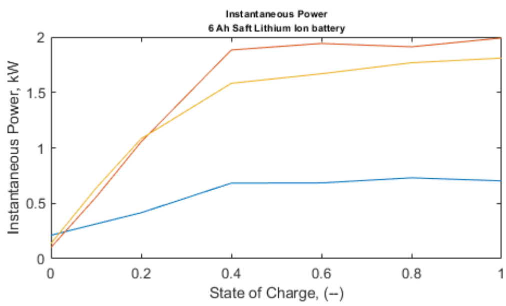


Figure 11(b) Li-ion Battery

Figure 11(b) shows that with SoC approaching to 1, the Power rises in conjunction with the temperature of the battery and Ohmic Resistance, and age.

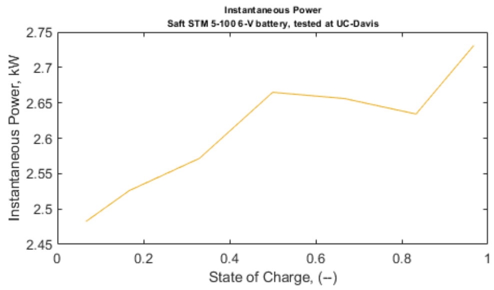


Figure 11(c) NiCd Battery

Figure 11(c) shows that with SoC approaching to 1, the Power first rises in proportionality, then in gradually decreases to an extent, and further climbs in direct proportionality.

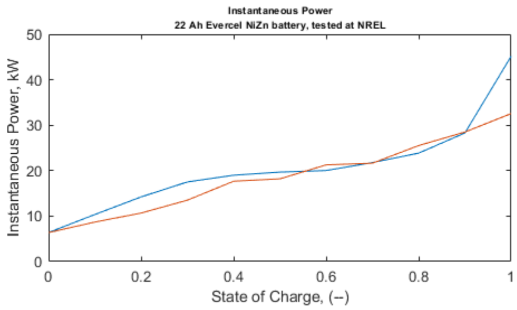


Figure 11(d) NiZn Battery

Figure 11(d) shows that with SoC approaching to 1, for a normal battery, the Power first rises in proportionality but for a new battery, this graph climbs up exponentially saving more energy immediately after 80% SoC.

Considering Fig 11(a) to 11(d), we can come to a conclusion that the battery pack power rises, with rise in State of Charge of an eV Battery.

D. Thermal Efficiency

Fig. 12 shows algorithm to determine the attitude of Thermal Efficiency with SoC approaching from 0 to 1 in a Battery Pack, as designed in MatLab.

Figure 12 depicts an algorithm to find out variation in thermal efficiency with varying Current. To determine this, varying current will be input in Q_{ess_gen} and the output shall be received at Q_{air} & T_{ess}.

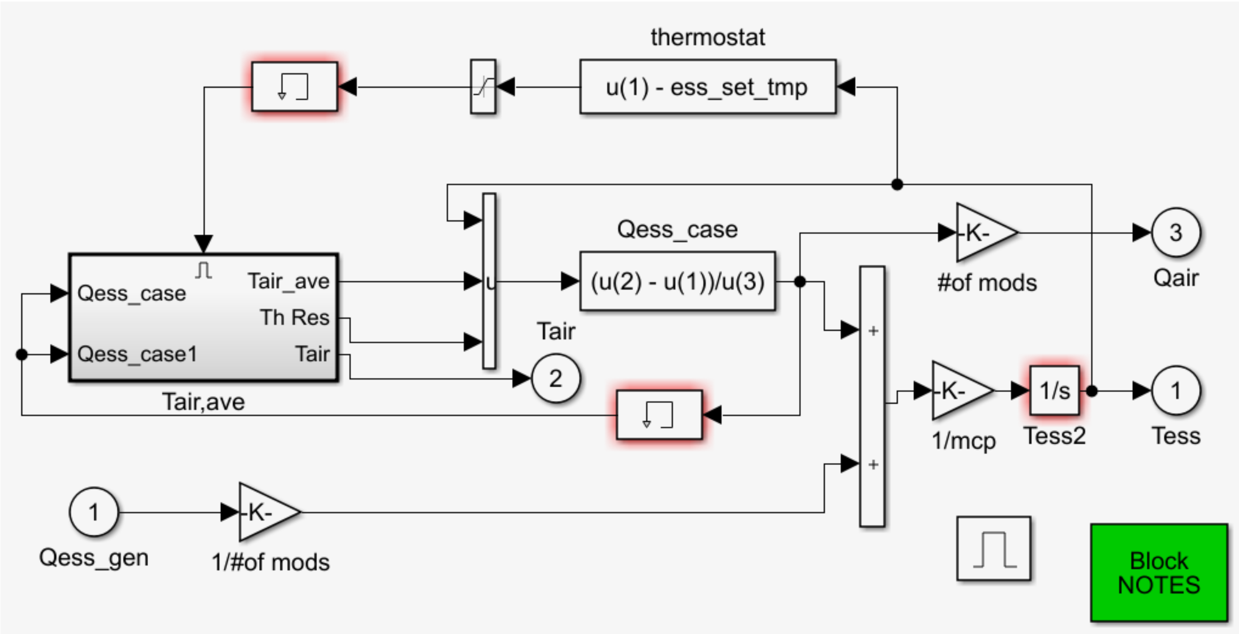


Figure 12 Algorithm for determining Battery Pack thermal efficiency

The thermal efficiency can be found out using the formula:

$\eta = [T_{ess}] / [Q_{air}]$

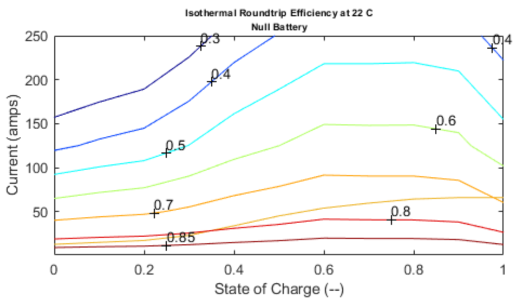


Figure 12(a) Lead Acid Battery

Figure 12(a) shows that with SoC approaching to 1, the thermal efficiency rises with rise in Current.

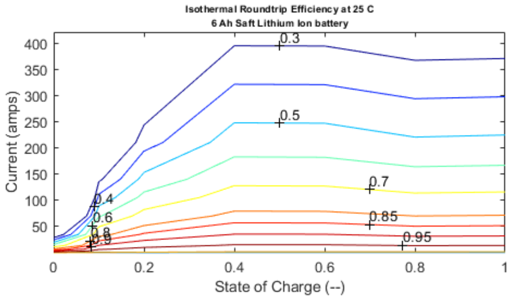


Figure 12(b) Li-ion Battery

Figure 12(b) shows that with SoC approaching to 1, the thermal efficiency rises with rise in Current.

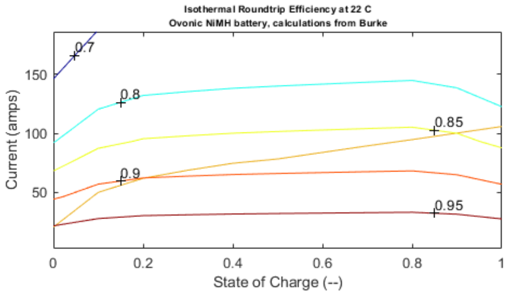


Figure 12(c) NiMH Battery

Figure 12(c) shows that with SoC approaching to 1, the thermal efficiency acts parabolic with rise in Current.

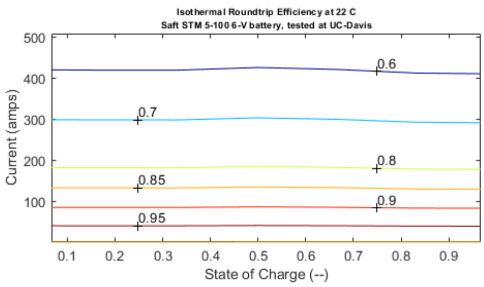


Figure 12(d) NiCd Battery

Figure 12(d) shows that with SoC approaching to 1, the thermal efficiency stays constant with rise in Current.

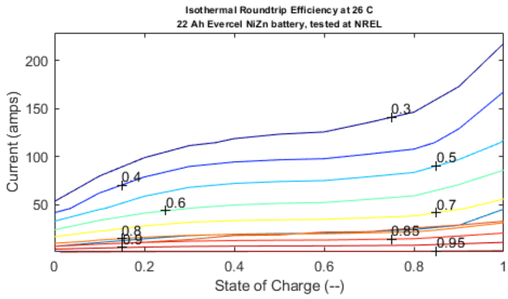


Figure 12(e) NiZn Battery

Figure 12(e) shows that with SoC approaching to 1, the thermal efficiency first rises gradually till 80% SoC and then exponentially with rise in Current.

This implies that the Thermal efficiency is independent of Battery current.

7. Next Generation Batteries: Sodium-Ion (or Sodium-Beta)

A. Introduction

The first Sodium-ion battery was invented by Ford Motors in the late 1960s to promote electric mobility, but soon it was also accepted for use in high scale storage applications for use in electric grids (Zhou *et al.*, 2013; ECOFYS, 2014; Zhang *et al.*, 2014). Besides being cheap, the widespread use of this battery is attributed to characteristics like its high-temperature utility of 300-350 degrees (Dincer and Rosen, 2002; Akhil *et al.*, 2013; Zhang *et al.*, 2014), the high energy density of 150-240 W h/kg, and high-power density of 150-230 W/kg (Chen *et al.*, 2009; Atwater and Dobley, 2011), long life of 4500 cycles (Lee *et al.*, 2013; ECOFYS, 2014), and also its high efficiency of energy of about 85-90% (Chen *et al.*, 2009; Atwater and Dobley, 2011; Cotterman, 2013; Zhou *et al.*, 2013). But apart from this, the battery also faces Sodium corrosion internally, and needs to be heated to about 320 degrees C, to maintain a functional molten state of the electrode (Dincer and Rosen, 2002; Zhou *et al.*, 2013), and also develops high resistance to the flow of electricity (Atwater and Dobley, 2011).

These are the only batteries, which use Solid-Sodium electrolyte as an anode. As a part of electrolyte, these batteries utilize beta-alumina that is (β″-Al2O3) since it has a good Sodium-ion conductivity at higher temperatures (Akhil *et al.*, 2013). These batteries are divided into Sodium-Sulphur and Sodium-halide following cathode materials (Atwater and Dobley, 2011; Akhil *et al.*, 2013).

B. Construction

This Sodium-Sulphur battery employs molten solid-Sodium in Anode, and molten Sulphur as Cathode, differentiated or partitioned with the help of solid Beta-Alumina ceramic-electrolyte (Zhang *et al.*, 2014). The chemical reaction taking place in the Sodium-Sulphur battery is as follows:

$$Na \quad + \quad {}_xS \quad \rightleftharpoons \quad Na_2\,S_x$$

where x = 3-5

C. Working

During discharging, Sodium-beta interface, and liberates positive Sodium ions, which further pass through the electrolyte of beta-alumina and reacts with Sulphur, to produce Sodium Polysulfides (Na_2Sx). On the contrary, the electro-chemical reaction reverses while charging the battery (Chen *et al.*, 2009; Atwater and Dobley, 2011; Akhil *et al.*, 2013; Zhang *et al.*, 2014).

With the advent of the 1990s, another battery technology, with voltage, even higher than Sodium-Sulphur entered the electric vehicle market, named Solium – metal – Halide. This technology had a high energy density and was resistant to corrosion. Further research in this battery technology led it to be called as 'Zero Emission Battery Research Activity (ZEBRA) (Akhil *et al.*, 2013; Tie and Tan, 2013). These batteries are also recognized for their wide operating temperature range. One such battery is Sodium-metal-chloride (Na-MeCl2) with an operating temperature range of 260-310 degrees Celsius. Besides this, Na – S uses a semi-solid cathode, so it has better clearance about over-charging and over-discharging as compared to Na-S, coupled with additional advantages like a better life span, and lower initial and maintenance cost (Atwater and Dobley, 2011; Tie and Tan, 2013; Zhang *et al.*, 2014). Apart from this, these batteries have a lower specific power which can go up to 200 W-kg, and a very poor thermal management and self-discharge (Chau, Wong and Chan, 1999; Tie and Tan, 2013; Zhang *et al.*, 2014; Hosseinifar and Petric, 2016).

If compared, the point that distinguishes these two sodium-ion or sodium-beta batteries is only the sodium aluminium-tetrachloride (Na-Al-Cl_4) which is used in ZEBRA Batteries as an electrolyte (Atwater and Dobley, 2011). Apart from this, ZEBRA Batteries utilize Sodium (molten) as an anode, a porous metal chloride (MeCl2) as a positive cathode, solid beta-alumina ceramic as a primary electrolyte, sodium aluminium tetrachloride (NaAlCl4) (molten) as a secondary electrolyte (Lv *et al.*, 2015) (Hannan *et al.*, 2017). Here, NiCl2, FeCl2, or a combination of the two, i.e. NiFeCl2 may be used as the metal chloride. The chemical equation so formed in this Ni-S battery is as follow:

$$2Na + NiCl_2 \rightleftharpoons Ni + 2NaCl$$

D. Charging & discharging:

The process of charging and discharging is similar to that of Na-S battery. During discharging, the Sodium and Nickel Chloride form Sodium Chloride and Nickel and while charging, this reaction reverses (Akhil *et al.*, 2013), as indicated in the above reaction equation. And in case of an overcharging, as depicted in the following equation, the $NaAlCl_4$ reacts with the Nickel (of primary electrolyte) and forms Nickel Chloride, Sodium in molten form and Aluminium-trichloride (Atwater and Dobley, 2011; Akhil *et al.*, 2013).

$$Ni + 2NaAlCl_4 \rightarrow NiCl_2 + 2Na + 2AlCl_3$$

E. Business Scope

With these properties, Reliance New Energy Solar Ltd (RNESL) bought Faridon, a UK based startup for $134 Mi, and plans to shift Faridon's state of the art setup to its Dirubhai Green Energy Giga Complex, Jamnagar (Alex, 2022).

F. How Sodium-ion battery supersedes all other batteries (including Lithium-ion battery)

Sodium-ion is the next generation ESS, attributed to the following reasons (Saumya, 2022) :

a. Sustainability : Sodium is sixth most abundant element on planet earth unlike Copper, Lithium, etc.

b. Cost – effective : The total Cost of extraction, processing and ownership of Sodium-ion battery is very less than any other battery material.

c. Charging & Discharging : Sodium-ion battery charges faster discharges slower than Li-ion battery.

d. Thermal capabilities : Sodium-ion battery can work on a wideroperating temperature range of -30° to +60° C.

e. Specific Energy : The specific energy of Sodium-ion is at par with Lithium-ion batteries and reach around 160 Wh/kg.

f. Overall comparison between Sodium-ion, Lithium-Nickel Manganese Cobalt, Lithium-Iron Phosphate and Lead acid batteries

Hence if Sodium-ion batteries substitutes Lithium-ion batteries, the production of battery material could be lowered by 41% per GWh energy (Saumya, 2022).

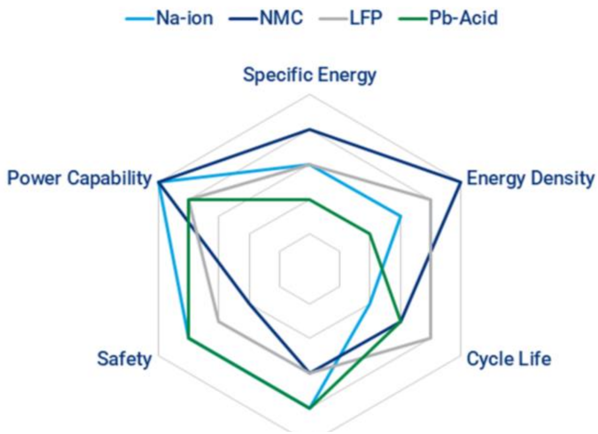


Figure 13 Performance Characteristics of batteries (Source : Wood Mackenzie(Wood Mackenzie, 2021))

8. Results

Considering the experimental work in this study, we can conclude the following:

a. The Internal resistance of different batteries behave differently with independent variations in SoC & Temperature.

b. In all the batteries, the Voltage is in direct proportion with the SoC.

c. In all Batteries, the Instantaneous power inside a battery is proportional to the State of Charge inside the battery.

d. Different batteries behave differently for Thermal Efficiency testing with varying Current.

9. Further Scope of Future Work

As we approach Electric vehicle technology, we intend to reduce the burden on the environment and therefore move to a greener India. But considering the factor that these batteries also pose harmful effects, the following are some challenges for the future:

a) Environmental friendliness – While production, these batteries emit some gases, that may lead to respiratory, neuro and pulmonary diseases (Dunn *et al.*, 2012; Gaines, 2014). Also after its usage, the final disposal should be done very cautiously(Emadi *et al.*, 2005; Hacker *et al.*, 2009; Omar *et al.*, 2012). Hence the batteries need to be processed so that these are environmentally friendly, to support the human race.

b) Ways to Fast Charging – Till now, there are only two ways of charging, namely charging on station and swapping of battery (Balasingam, Ahmed and Pattipati, 2020). The charge on the station is usually a cheaper way, but it takes a lot of time, even with fast charging hence is inconvenient (Mishra *et al.*, 2021). Therefore, governments must look ahead to the adoption of battery swapping technology.

c) Cost of ownership of Battery – Today in India, the running cost of an Electric Vehicle is lesser, but in contrast, the initial cost is too high. The same goes with the battery module, the initial cost is too high (Kumar *et al.*, 2020). And a stable model is required, that can capture the non-linear behaviour of the relationship between the consumption of electricity and its associated prices (Vasant, 2019). Therefore, there is a high need of popularizing the advantages of these electric vehicles, as well as some subsidies from the governments shall be highly solicited for promotion.

d) Human Safety – The utilization of a battery can be disastrous if exploited and not used appropriately, causing fire, shock, etc. Therefore, such amendments and standardizations are yet to be implemented in Automotive India Standards, AIS-038 (Malik and Vashist, 2022)

e) Behaviour in different environmental conditions – The performance changes in different environmental conditions, about the pressure, the temperature of exchange of ions or otherwise chemical reactions. (Vashist, Pandey and Malik, 2023). The solution may be an in-depth study of such reactions in detail.

10. Conclusion

Different battery chemistries that are suitable for Indian market conditions are analyzed. The different chemistries that were taken for study include Lead Acid, Nickel, Zinc Halo, Metal-air, Lithium-ion, and these batteries were made to run on Advisor software (MATLAB) where their characteristics were determined with predefined specifications of a virtual vehicle.

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