PERFORMANCE STUDY OF DIFFERENT TYPES OF BATTERY OF ELECTRIC VEHICLES

by

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CERTIFICATE OF APPROVAL

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DECLARATION

It is hereby declared that this work has been done by us and no portion of the work contained in this thesis/project has been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

Fossil fuel and internal combustion engines are the backbone of our transportation and energy need since the industrial revolution. However, this extreme usage of fossil fuel over the period of last 200 years comes back to us with some extreme consequences of global warming, drastic change of environment, melt of glacier, rise in sea level, draut and many more. Scientists are looking for solutions to replace fossil fuel based transportation system for a long time now. In this path, electric vehicle (EV) was an important introduction to solve the problems of current transportation system. Although the concept of EV is old enough but the mass production and use of complete EV cars was delayed due to not having suitable battery or energy storage system for the EV up until the beginning of 21st century. Energy storage system plays the vital role in EV. Currently there are three main stream EVs - hybrid electric vehicle (HEV), fuel cell vehicle (FCV) and battery electric vehicle (BEV or EV). In this work, we have analyzed different types of battery performance of battery electric vehicles. We have thoroughly studied various types of batteries such as Nickel metal-hydrate, Zinc hybrid-cathode, lead acid, lithium ion and so on. A MATLAB Simulink based electric vehicle has been designed to evaluate the performance of the batteries. The performance parameters have been evaluated for all the batteries.

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LIST OF ABBREVIATIONS

EV	Non-superconducting Electric vehicle
HEV	Hybrid electric vehicle
FCV	Fuel cell electric vehicle
BEV	Battery electric vehicle
GDI	Gasoline direct injection
LNG	Liquefied natural gas
Ni-MH	Nickel metal hydride
Li-ion	Lithium ion

CHAPTER 1

INTRODUCTION

1.1 Introduction

We have been using fossil fuels as the backbone of our transportation system since the invention of steam engine and internal combustion engine. Modern civilization and transportation system largely dependent on these engines and fuels. But in the core of our transportation system there are some key problems such as -

1. very low efficiency of these engines by their nature.
2. extreme environment impacts
3. future shortage of fossil fuels.

These problems are so vital that without solving them, our civilization might come to a halt. Hence many solutions are being thought throughout last couple of decades. Electric vehicle (EV) is one of them and one of the most prominent ones obviously. The main parts of an EV are battery, motor drive, motor and controller. The difference between EV and conventional vehicle is -

Firstly, EV use direct electrical power as fuel, on the other hand conventional vehicle use fossil fuels for powering the vehicle.

Secondly, EV use motor to rotate the wheels while conventional vehicle uses internal combustion engines to rotate the wheels. So, we can say that battery is the backbone of an EV. In the development phase of EV, battery plays a vital role because mileage of an EV dependent on the battery size of that EV. But adding a huge battery pack in an EV significantly increase the weight of the EV. Battery size represented in Wh/kWh per unit weight of a specific type of battery is presented with the term specific energy of a battery. Specific energy along with other parameters has become important factors to choose a battery for EV

1.2 Problems of current transportation system

FCVs fueled by pure hydrogen release no toxic emissions, which contribute to smog and dangerous particles in the United States. Some pollutants are produced when hydrogen is produced from fossil fuels, although they are far fewer than those produced by conventional cars [1].

At the moment, FCVs are more expensive than traditional automobiles and hybrids. Costs, on the other hand, have dropped dramatically and are approaching the DOE's 2020 target (see graph). To compete with conventional automobiles, carmakers must continue to reduce prices, particularly for the fuel cell stack and hydrogen storage [2].

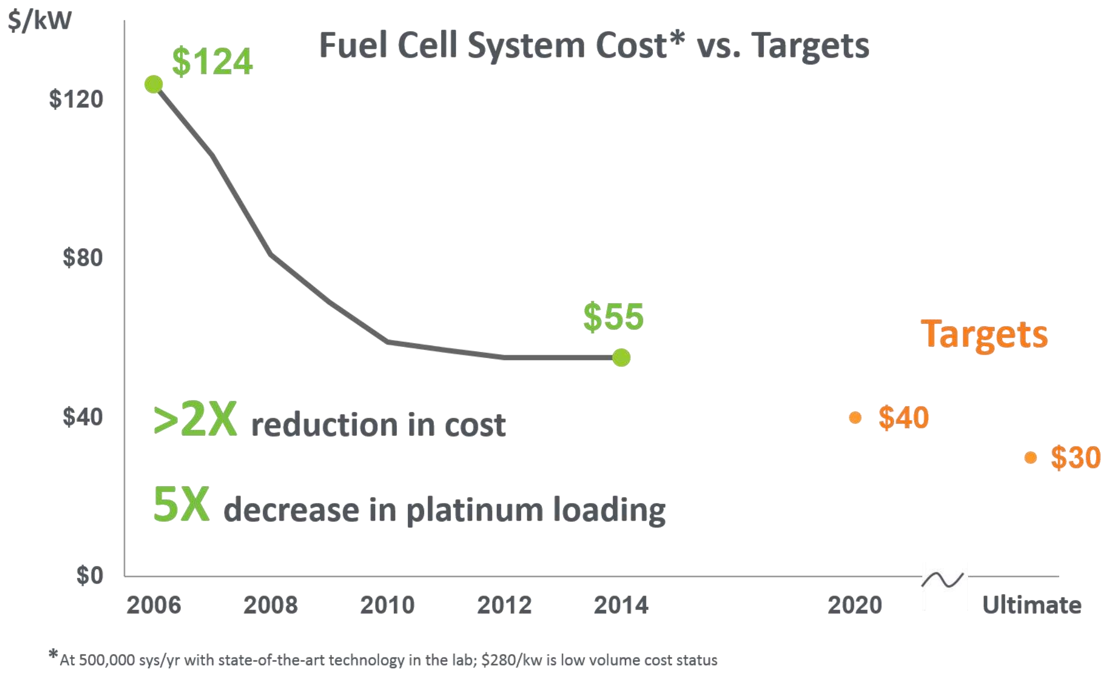


Fig. 1.1 Fuel Cell System Cost Progress [1].

The present infrastructure for manufacturing and delivering hydrogen to customers is insufficient to allow wide-scale deployment of FCVs. H2USA was established in 2013 as a public-private cooperation involving the Department of Energy and other federal agencies, as well as automakers, state governments, academic institutions, and other stake-holders. Its mission is to coordinate research and find cost-effective hydrogen infrastructure deployment options. More than 50 public stations, largely in California, should be ready by the end of 2015. This is a critical first step towards making hydrogen available to the general public.

In various temperature and humidity ranges, fuel cell devices are not as robust as internal combustion engines. The durability of on road fuel cell stacks is now roughly half of what is required for commercialization. Although durability has improved significantly in recent years, from 29,000 to 75,000 miles, experts predict FCVs will need to reach a 150,000-mile projected lifetime to compete with gasoline cars.

Before the benefits of FCVs can be realized, customers must accept them. When these cars initially enter the market, people may have reservations about their dependability and safety, as with any new automotive technology. They also need to learn how to use a new type of gasoline. This process can be accelerated by public education.

Meanwhile, America’s ravenous thirst for oil continues to exacerbate a rising national security concern: climate change. Oil combustion is one of the greatest sources of greenhouse gas emissions and hence a key cause of climate change, which, if allowed un- controlled, may have grave security repercussions worldwide. Burning oil from "risk or unstable" nations alone produced 640.7 million metric tons of carbon dioxide into the sky, the equivalent of driving over 122.5 million passenger cars.

According to recent studies, the worst effects of climate change could destabilize governments, intensify terrorist attacks, and displace hundreds of millions of people as a result of more frequent and severe natural disasters, higher rates of diseases like malaria, rising sea levels, and food and water shortages.

According to a 2007 study by the Center for American Progress, climate change might have far-reaching social, political, and environmental ramifications, including "destabilizing levels of internal migration" in poorer nations and more immigration to the United States. To cope with these situations, the US military will be under increased strain, putting our troops in jeopardy and requiring already stretched resources to be dispatched abroad.

Natural disasters exacerbated by global warming, such as Hurricane Katrina in the United States and the Indian Ocean tsunami in 2004, would necessitate military assistance. Because wealthy nations are better equipped to adapt to climate change, the world’s poor will be most at danger. Aid efforts, as well as reacting to crises caused by climate-induced mass migration, will be the responsibility of developed nations.

1.2.1 Engine efficiency

A multitude of losses occur during the conversion of fuel energy into usable work in an internal combustion engine. Figure 1.2 depicts the principal engine energy losses as well as the associated efficiency factors. In the literature, there are further research on the factors that impact engine efficiency, with an emphasis on Low Temperature Combustion [3].

A tiny portion of fuel does not entirely convert to the ideal combustion products CO_2 and H_2O when a hydrocarbon fuel is burned and its energy is released. The combustion

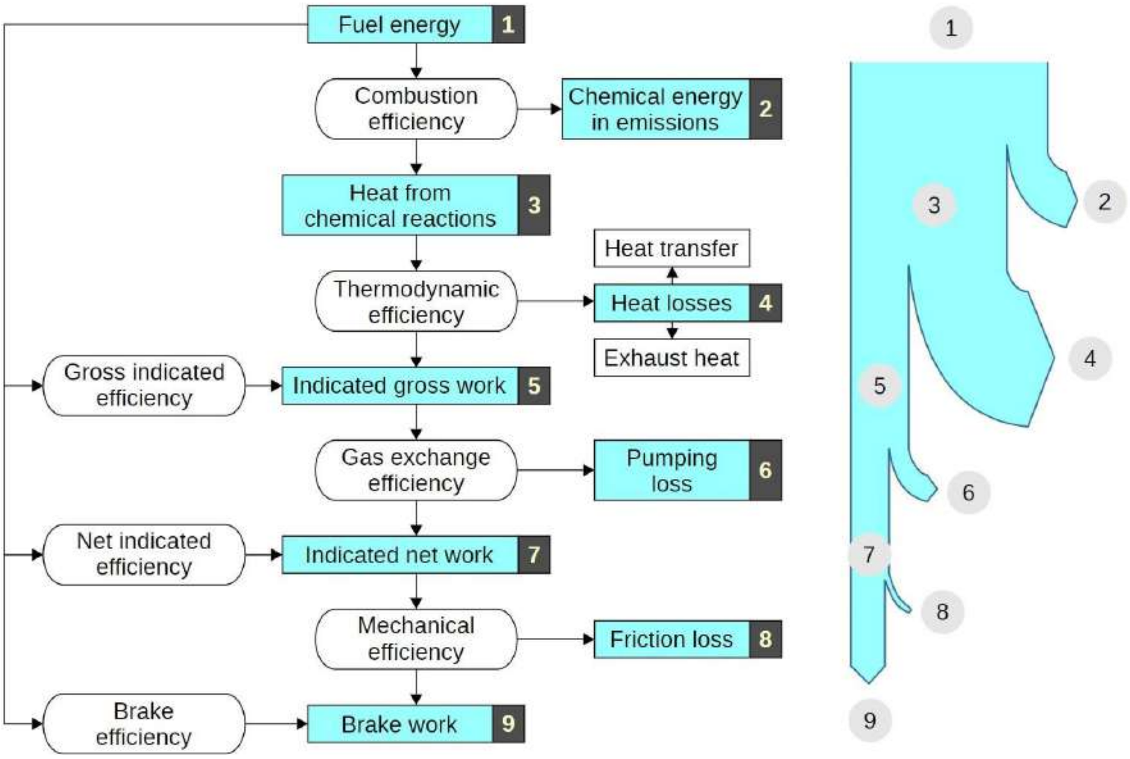


Fig. 1.2 Overview of energy losses in a typical internal combustion engine [3]

efficiency accounts for the energy left in the unburned fuel and combustion intermediates [4].

Only a percentage of the energy generated by the combustion process can be transformed into meaningful work, according to the second rule of thermodynamics. This proportion is accounted for by the thermodynamic efficiency, which is determined by the characteristics of the heat-to-work cycle. The highest limit of thermodynamic efficiency for internal combustion engines is commonly calculated using Otto and Diesel cycle calculations. Heat is lost as a result of combustion energy that is not transformed into mechanical effort, either through the release of hot exhaust gases into the atmosphere or by heat transmission through the combustion chamber surfaces. The entire work produced by the burning of the fuel is represented by the gross indicated efficiency, which is equal to the product of combustion efficiency and thermodynamic efficiency [5].

Some of the energy that has been transformed into work is utilized to induct intake gases and expel exhaust gases from the engine. The gas exchange efficiency is used to account for this pumping loss. The net indicated efficiency subtracts the effort necessary to transfer gases into and out of the engine from the gross indicated efficiency.

Unfortunately, even with routine automobile maintenance like a tune-up or an oil change, today's gasoline engines are only 30 to 35 percent efficient, which means that 65 cents of every dollar spent on petrol is wasted.

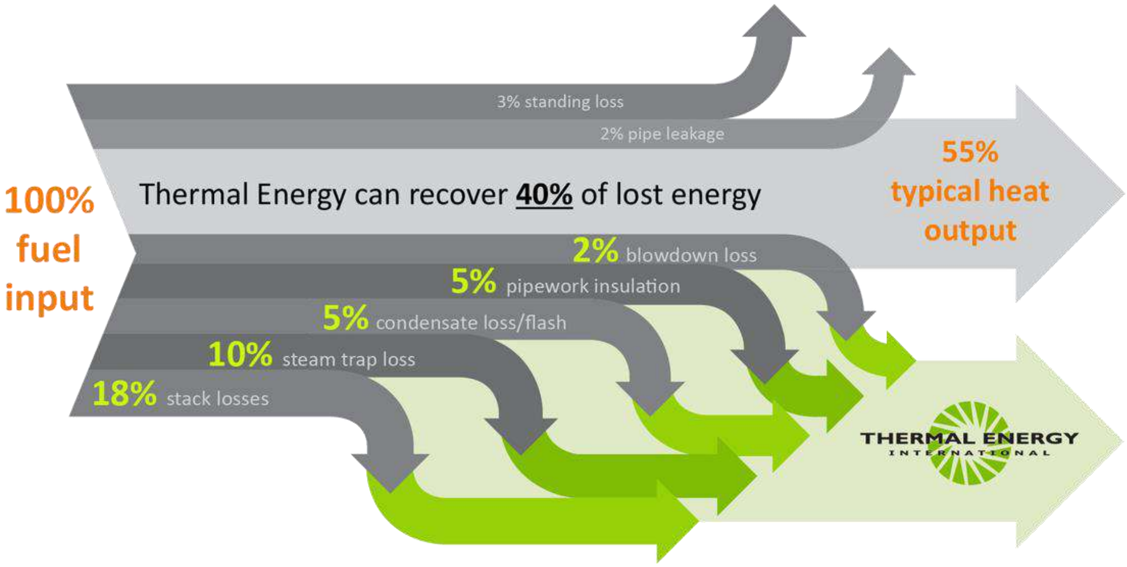


Fig. 1.3 Mechanical Steam Traps Which Open When Water Is Present - Thermal Energy Clipart [6].

Many moving elements in an engine cause friction. Some of these friction forces remain constant (as long as the applied load remains constant); others, such as piston side forces and connecting bearing forces, rise as engine speed increases (due to increased inertia forces from the oscillating piston). At greater speeds, some friction forces diminish, such as the friction force on the cam lobes used to control the inlet and exit valves (the valves' inertia pulls the cam follower away from the cam lobe at high speeds). Pumping losses, or the labor required to get air into and out of the cylinders, are also present in a running engine. At low speeds, this pumping loss is negligible, but it grows as the square of the speed until an engine is utilizing around 20% of total power generation to overcome friction and pumping losses at rated power.

In most steam systems, 55% of the usable energy produced by the fuel input is used. The remaining energy is wasted as a result of inefficiencies such as stack and blow down losses, steam trap losses, condensate flashing, and other energy losses shown in Fig.1.3. To release this water, mechanical steam traps have traditionally been used, which open when water is present and close when steam is present. Mechanical traps are the Achilles heel of the steam system because of its moving parts, which are prone to seizure and failure. As a result, they are a persistent source of energy losses and operational problems [7].

1.2.1.1 *Gasoline (petrol) engines*

Contemporary gasoline engines have a maximum thermal efficiency of more than 50%, while road legal automobiles have a thermal efficiency of about 20% to 35% when utilized to power a vehicle. In other words, even when the engine is functioning at its point of maximum thermal efficiency, of the entire heat energy created by the gasoline consumed, roughly 65-80 percent of total power is expelled as heat without being transformed into usable work, i.e. spinning the crankshaft. Approximately half of the rejected heat is transported away by exhaust gases, while the other half goes through the cylinder walls or cylinder head into the engine cooling system before being released into the atmosphere via the cooling system condenser. A few of the energy released by the fuel consumed is lost as friction, noise, air turbulence, and work used to turn engine equipment and appliances like water and oil pumps and the electrical generator, leaving only about 20-35 percent of the energy released by the fuel consumed available to move the car.

The petrol car burns a mixture of gasoline and air with a ratio of roughly twelve to eighteen parts air to one component fuel (by weight) (by weight). Stoichiometric means that when a combination with a 14.7:1 air/fuel ratio is burnt, 100% of the fuel and oxygen are used. Lean burn mixtures, which use somewhat less fuel, are more efficient. Combustion is a reaction in which oxygen in the air reacts with the fuel, which is a combination of various hydrocarbons, producing water vapor, carbon dioxide, and occasionally carbon monoxide, as well as partly burnt liquid fuels. Furthermore, oxygen prefers to mix with nitrogen at high temperatures, resulting in nitrogen oxides (usually referred to as NOx, since the number of oxygen atoms in the compound can vary, thus the "X" subscript). The exhaust contains this combination, as well as any remaining nitrogen and other trace atmospheric components.

GDI (Gasoline Direct Injection) improved the efficiency of engines equipped with this fueling technology by up to 35% between 2008 and 2015. As of 2020, the technology can be found in a wide range of cars [3].

1.2.1.2 *Diesel engines*

Even though the Diesel cycle is less efficient at equal compression ratios, engines that use it are generally more efficient. Because diesel engines have significantly greater compression ratios (the heat of compression is utilized to ignite the slow-burning diesel fuel), the higher ratio more than compensates for the engine’s air pumping losses.

To improve economy, modern turbo-diesel engines employ electronically controlled common rail fuel injection. This also boosts the engines’ torque at low engine speeds with the use of a geometrically variable turbo-charging system (although with extra maintenance) (1200-1800 RPM) [3]. Low-speed diesel engines, such as the MAN S80ME-C7, have a 54.4 percent total energy conversion efficiency, the greatest of any single-cycle internal or external combustion engine. Large diesel trucks, buses, and modern diesel automobiles have engines that can reach peak efficiency of 45% approximately [5].

1.2.2 Future fuel crisis

In the last year, the price of gasoline in the United States has risen by more than 50%. During the same time span, the price of natural gas in Europe has risen by nearly 500%. According to a Bloomberg story, Asian power firms are buying liquefied natural gas at record levels to ensure a steady supply.

Due to growing energy prices, a large European fertilizer company has already been forced to temporarily shut down two plants in the United Kingdom, and there are worries that more industries may fall into line.

The US Energy Information Administration has issued a study warning that Americans would most likely have to pay much more to remain warm this winter, especially if temperatures drop.

Fundamental economics’ demand-supply formula can offer you a good notion.

There is a shortage of commodities and price hikes when demand exceeds supply. Prices fall as supply increases, while prices rise when supply decreases. A similar dynamic is occurring: energy demand is outstripping supply, resulting in price increases.

Several reasons, including the pandemic, inadequate government policies, and climate change, are undoubtedly to blame for this abrupt increase. Many countries have stopped investing in fossil fuels (for a number of reasons), resulting in a decrease in their availability. However, we currently lack sufficient renewable energy to totally replace fossil fuels. We’ll do it eventually, but not right away. In 2019, the three primary fossil fuels, oil, coal, and natural gas, accounted for almost 80% of global energy consumption. While wind supplied slightly more than 2% of total energy consumption, solar contributed slightly 1% more than [8].

Wind and solar output and distribution would need to increase by 2,500 percent to completely replace fossil fuels, which is unlikely to happen in the next few years. We require a transitional plan. We will face a severe energy problem if we don't have it. Because industrialized civilizations cannot function without regular access to energy, governments do everything possible to keep the lights on when these shocks occur. Germany, for example, has built a world-class renewable energy source over decades. However, despite the fact that fossil fuels provided 56 percent of total power in Germany in the first half of 2021, the government is striving to phase out their use [9].

During the same time span, however, coal-based power output in Germany increased from 21% to 27%, with all other fossil fuels remaining unchanged. Global energy policy contradictions have gotten so bad that they're nearly comical. China, for example, has banned Australia's coal imports. While switching from coal to natural gas may be better for the environment, China, Japan, and South Korea have all acquired large quantities of LNG, driving up market costs. Floods in China's eastern coal mines also disrupted much of the country's coal output, restricting energy generation and causing acute power shortages across the kingdom.

Because industrialized civilizations cannot operate without regular access to energy, governments do everything they can to keep the lights on when these shocks strike. Germany, for example, has built up a world-class renewable energy source over many years. However, despite the fact that fossil fuels provided 56 percent of total power in Germany in the first half of 2021, the government is working to phase out their use. During the same time span, however, coal-based power output in Germany increased from 21% to 27%, with all other fossil fuels remaining unchanged [9]. Global energy policy contradictions have gotten so bad that they're nearly comical. China, for example, has banned Australia's coal imports.

While switching from coal to natural gas may be better for the environment, China, Japan, and South Korea have all acquired large quantities of LNG, driving up market costs. Floods in China's eastern coal mines also disrupted much of the country's coal output, restricting energy generation and causing acute power shortages across the country. The switch from coal to gas, for example, was responsible for the bulk of CO2 reductions in the US between 2005 and 2019. We could be able to easily afford to convert those 1,400 plants and save a large amount of carbon. In addition, according to the International Energy Agency, current methods can avoid over 70% of methane leakage from production of oil and gas.

The objective must be to use renewable energy sources to power the entire planet. The cost of solar and wind energy has plummeted dramatically in recent years, which is great news for the world’s population. They are now more accessible than they have ever been to the general people. As batteries get more powerful and other storage options gain momentum in the marketplace, storage, which has previously been a key concern with these intermittent sources, is now being addressed. Although genuine progress is being made, the amount of money spent on research and development in this subject has to be greatly boosted.

We must, however, continue to cut emissions today while ensuring a sufficient supply of energy. If this does not happen, we may face further energy crises in the future, potentially leading to a backlash against environmental rules. Governments need to be aware of the global energy dilemma and make a coordinated effort to maintain the world ecosystem healthy. [8].

1.2.3 Environment Problem

Global warming offers major environmental, social, political, and military concerns that we must address in the interest of our own defense, according to military and intelligence specialists. Climate change is being included as a security issue in the Pentagon’s 2010 Quadrennial Defense Review, a study required by Congress every four years that updates Pentagon priorities. Climate change will be included as a national security issue in the State Department’s Quadrennial Diplomacy and Development Review. In September, the CIA established the Center on Climate Change and National Security to advise policymakers on the implications of global warming on national security.

Prominent Iraq and Afghanistan combat personnel also support climate and clean-energy measures because they see the need of such reform for our safety. "We realize that climate change is already harming destabilized states with unstable governments," Jonathan Powers, an Iraq war veteran and chief operations officer for the Truman National Security Project, stated. That is why hundreds of veterans from practically every state have joined Operation Free, knowing that it would be our troops that will have to act in those weak states, against those extremist groups."

"Climate change can function as a danger multiplier for instability in some of the world’s most volatile locations, and it poses serious national security issues for the United States," the CNA Corporation’s Military Advisory Board said in 2007. CNA determined that climate change, energy reliance, and national security are all interconnected problems in an update of its 2007 study released last year.

The research, titled "Powering America’s Defense: Energy and the Risks to National Security," reiterates the conclusion that our reliance on fossil fuels jeopardizes our national security. "Overdependence on imported oil—by the United States and other countries—tethers America to unstable and unfriendly regimes, subverts foreign policy aims, and necessitates the United States to expand its military presence around the globe," the board finds.

"Given the national security vulnerabilities posed by America’s existing energy posture," according to CNA, "a substantial transformation in energy policy and practice is essential."

1.3 Solution to these problems

Diesel engines are getting more and more popular. A hybrid automobile is one that has two or more engines, one of which is an electric motor and the other is a normal engine (either petrol or diesel). The automobile is powered by an electric motor at low speeds and a gas engine at greater speeds. A hybrid automobile, such as the Toyota Prius and Honda Civic Hybrid, not only saves gasoline but also emits less CO_2.

Despite the fact that hybrid vehicles are becoming more popular, few people are actually utilizing them, owing to a lack of understanding of how they function and if they are as good as conventional internal combustion engine vehicles.

Whereas the technology has been there since the early 1900s, it has only been in the last decade or so that the cost of production has brought them within reach of the average motorist.

More government incentive schemes, like as tax credits and special discounts, are also available to encourage the purchase and usage of hybrid cars. As part of a drive to become more ecologically responsible, several communities are replacing their public transit and service vehicles to hybrid cars and buses.

Wikipedia defines hybrid vehicle as,

"A hybrid vehicle combines two or more distinct types of power, such as an internal combustion engine and an electric motor, as seen in diesel-electric trains that use diesel engines and electricity from overhead lines, and submarines that use diesels when on the surface and batteries when submerged." Pressurized fluid, used in hydraulic hybrids, is another way to store energy [9].”

1.3.1 Efficient electric vehicle engine

Hybrid vehicles have two engines. The gasoline engine, which is the principal source of power, is significantly smaller than those found in single-engine vehicles, and the electric motor is quite weak. Both engines have less combined power than a gas-powered engine. As a result, it is best suited for city driving rather than speed and acceleration. Over all relevant engine loads and speeds, electric motors have a better tank-to-wheel efficiency (73–90%) than internal combustion engines (16–37%). Electric cars, unlike conventional vehicles, recover their kinetic energy through regenerative braking.

1.3.2 Electricity and renewable sources

Next-generation transportation will be powered by electricity rather than fossil fuels, and the electricity generating industry is fast transitioning from fossil to renewable sources. Oil and gas, as indicated in Fig. 1.3, are expected to dominate the automotive-fuel energy scenario until 2030, according to respondents. While oil, natural gas, and biofuel/petroleum mixes will account for 95% of the energy used to power automobiles in 2017, this figure will drop to 67% by 2030. Hydrogen and electricity will account for more than half of all energy by 2070. Only 5% of the world’s vehicles will be powered by oil and gas after 2100 [10].

To summarize, although working entrepreneurs think that petroleum will continue to be the primary energy sources in the twenty-first century, the picture changes dramatically if we focus just on the transportation business. Respondents predict fossil fuel, electricity, hydrogen, and renewables will significantly replace oil in the next 20 to 25 years.

1.3.3 Environment friendly EV

One of the most huge advantages of a hybrid vehicle over a gasoline-powered vehicle is that it is cleaner to drive and has greater gas efficiency, making it more ecologically friendly. A hybrid car has two engines: a gasoline engine and an electric motor, which reduces fuel consumption and helps to conserve.

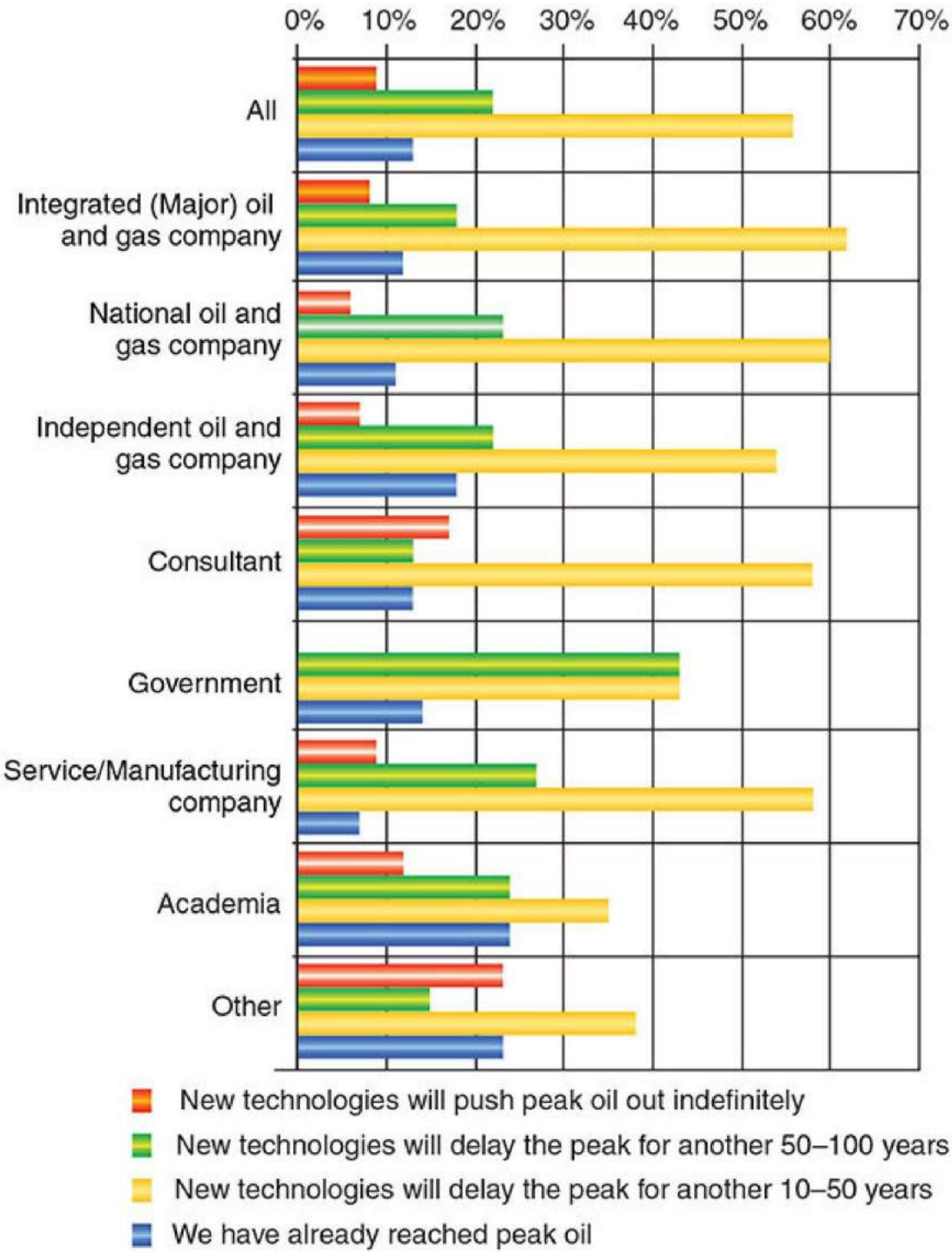


Fig. 1.4 What effect will new technology and renewable energy development have on the peak-oil timing? [10].

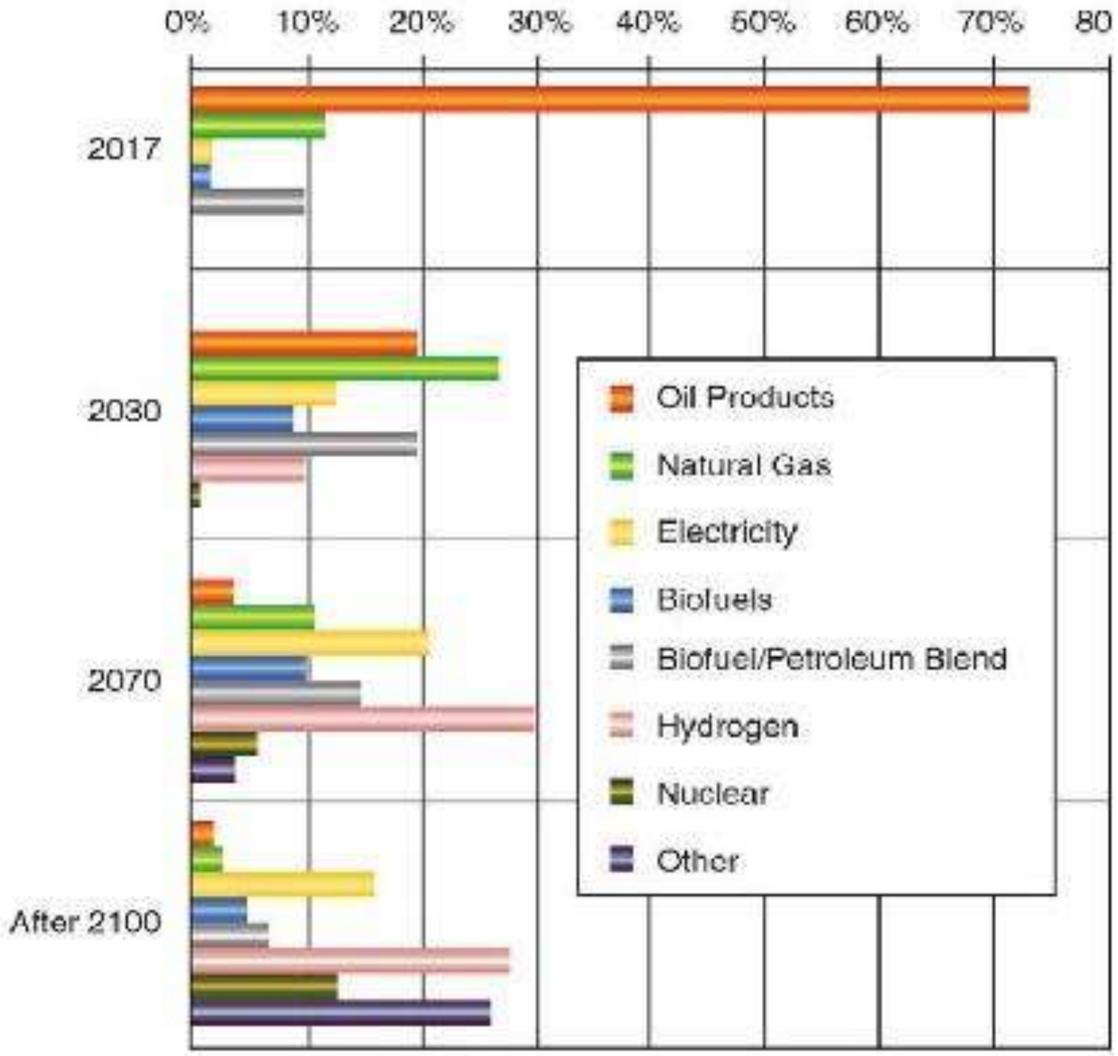


Fig. 1.5 What energy source do you see primarily powering cars by each of the following years? [10].

1.4 Objectives of this work

The key objectives of this work are -

1. We have studied the usage of battery in vehicles thoroughly. Our main focus was to study the different types of battery that are being used in EVs since the early introduction of EV. We have found 3 types of batteries were commonly used in EVs.
    - (a) We have thoroughly studied the performance parameters of the following batteries - lead acid, nickel metal hydrate, lithium ion, zinc hybrid cathode.
    - (b) Simulation of EV in Simulink
    - (c) Simulation of EV with lead acid, lithium ion and nickel metal hydrate battery to see the difference of the EV performance.
    - (d) Evaluation of simulation result as well as other literature review based data to find out the better performing battery.

1.5 Outlines of this thesis

This thesis paper has been organized in the following manner -

Chapter 1 presents motivation, background and objectives of this work. **Chapter 2** presents literature review of this work. A detailed overview of current and old batteries of EV is presented in this chapter. in **Chapter 3** the design and simulation of the EV in Simulink has been discussed. The simulation result and overall evaluation of this study is presented in **Chapter 4** and **Chapter 5** concludes this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Lead Acid Battery

In solar systems, lead acid batteries are the most popular form of battery. Despite their poor energy density, low efficiency, and high maintenance needs, lead acid batteries have a long lifespan and affordable prices when compared to other battery types. Lead acid batteries have the distinct benefit of being the most widely utilized kind of battery for most rechargeable battery applications (for example, starting vehicle engines), and hence have a well-established, mature technical basis [11].

Lead-acid batteries (Pb-PbO2). These are the oldest rechargeable batteries, having been created in 1859. This type of battery has been utilized in electric cars as well as in conventional automobiles. Its specific and energy density ratios are both quite low. A sulfuric acid deposit and a set of lead plates combine to make the battery.In the negative plates, lead sulfate is reduced to metal during the first loading process, whereas lead oxide is generated in the positive plates (PbO2). This type of battery was utilized in automobiles such as the GM EV1 and the Toyota RAV4 EV. The negative electrode of a lead acid battery is formed of spongy or porous lead. To aid in the creation and dissolution of lead, the lead is porous. Lead oxide makes up the positive electrode. Both electrodes are submerged in a sulfuric acid and water electrolytic solution. An electrically insulating but chemically permeable membrane separates the two electrodes in the event that they come into contact with each other due to physical movement of the battery or variations in electrode thickness. This membrane also protects the electrolyte from electrical shorting. The reversible chemical mechanism depicted below stores energy in lead acid batteries. The overall chemical reaction is:

$$PbO_2 + Pb + 2H_2SO_4 \underset{charge}{\overset{discharge}{\rightleftharpoons}} 2PbSO_4 + 2H_2O \tag{2.1}$$

At the negative terminal the charge and discharge reactions are:

$$Pb + SO_4^{2-} \underset{charge}{\overset{discharge}{\rightleftharpoons}} PbSO_4 + 2e^- \tag{2.2}$$

At the positive terminal the charge and discharge reactions are:

$$PbO_2 + SO_4^{2-} + 4H^+ \xrightleftharpoons[charge]{discharge} PbSO_4 + 2H_2O \qquad (2.3)$$

Discharging a battery results in the creation of lead sulfate crystals at both the negative and positive terminals, as well as the release of electrons owing to the change in valence charge of the lead, as shown by the equations above. The sulfate from the sulfuric acid electrolyte that surrounds the battery is used to make this lead sulfate. As a result, the concentration of the electrolyte decreases. Instead of sulfuric acid enveloping the electrodes after a full discharge, both electrodes would be coated with lead sulfate and water. There is no chemical potential or voltage between the two electrodes at full discharge since they are made of the same material. Discharging, on the other hand, ceases much before the cutoff voltage.

A lead acid battery's voltage will gradually decrease between the totally depleted and charged stages. The state of charge of a battery is often expressed in terms of voltage level. The battery's dependency on its level of charge is depicted in the diagram below. Large lead sulfate crystals can form in the battery if it is kept in a low state of charge for a lengthy period of time, reducing its capacity permanently. These bigger crystals are difficult to convert back to lead because they lack the porous structure of a conventional lead electrode.

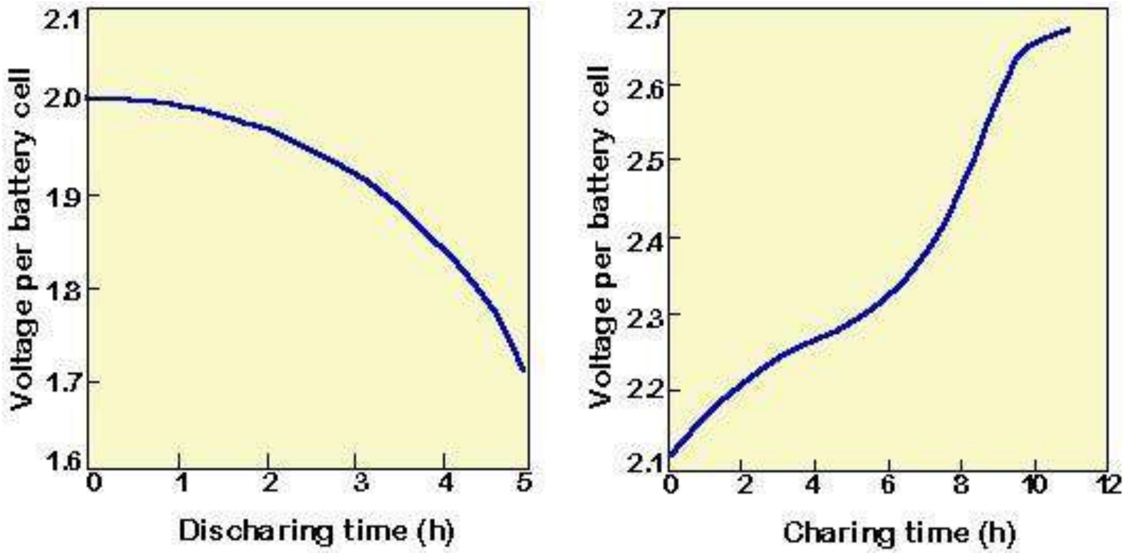
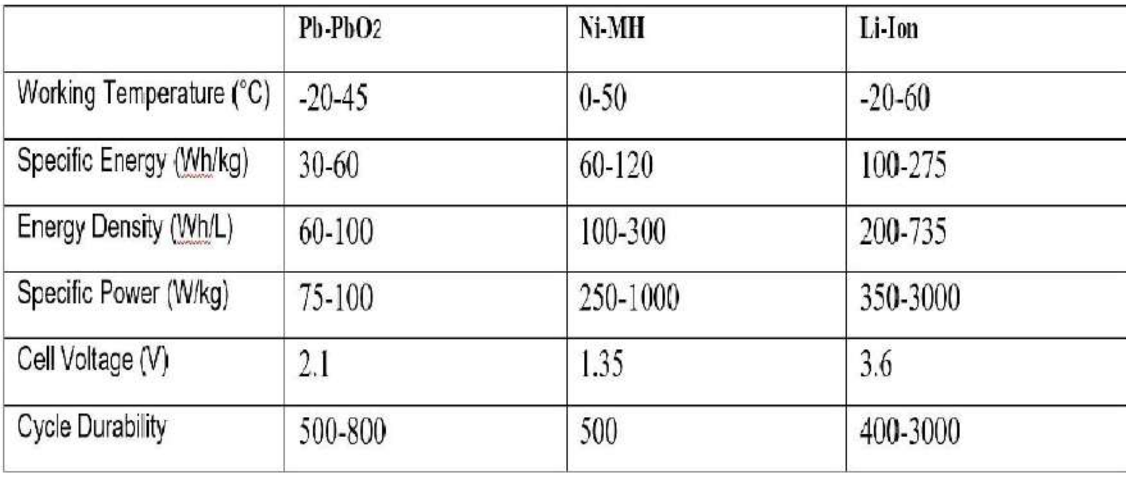


Fig. 2.1 characteristics curve of Discharging and charging time of Led Acid batteries [11].



	Pb-PbO2	Ni-MH	Li-Ion
Working Temperature (°C)	-20-45	0-50	-20-60
Specific Energy (Wh/kg)	30-60	60-120	100-275
Energy Density (Wh/L)	60-100	100-300	200-735
Specific Power (W/kg)	75-100	250-1000	350-3000
Cell Voltage (V)	2.1	1.35	3.6
Cycle Durability	500-800	500	400-3000

Fig. 2.2 Characteristics cooperation between lead-acid, NiMH, Li-ion [11].

2.1.1 Cost related parameters

Some of the parameters related to cost that were is in this paper is given is given here

Capital Cost ⇒ Cost per KWh/unit

AC/DC/AC conversion ⇒ Cost related to power conversion between AC and DC. AC/DC conversion cost largely depend on the size of the system.

Operation and Maintenance cost ⇒ it includes all maintenance cost during the full life cycle of the energy storage system. There are two types of cost included in this costing

1. Fixed cost
2. Variable cost

2.1.2 Performance related parameters

round trip efficiency(RTE) ⇒ charging and discharging efficiency.

Response time/ Ramp rate ⇒ time needed to reach a desired output level irrespective of the current state of the battery

Life cycle ⇒ how many charging and discharging can a battery sustain without losing too much depth of discharging (DoD). Here 80% DoD is considered.

Calendar life ⇒ maximum year a battery can operate without being used

MRL & TRL ⇒ MRL is the indication of how easily a battery can be manufactured as well as the current state of maturity of the particular battery during manufacture.

TRL - Technology readiness level.

Based on these parameters, **Table 2.1** has been made to compare all the technologies.

Table 2.1 Summary of all battery technologies [11].

	Lithium-Ion		**Lead Acid**		**Redox Flow**		**Sodium-Sulfur**		**Sodium-Metal Halide**		**Zinc-Hybrid Cathode**	
Parameter	2018	2025	2018	2025	2018	2025	2018	2025	2018	2025	2018	2025
Capital Cost–Energy Capacity ($/kWh)	271	(189)	260	(220)	555	(393)	661	(465)	700	(482)	265	(192)
Power Conversion System ($/kW)	288	(211)	350	(211)	350	(211)	350	(211)	350	(211)	350	(211)
Balance of Plant ($/kW)	100	(95)	100	(95)	100	(95)	100	(95)	100	(95)	100	(95)
Construction and Commissioning Cost ($/kWh)	101	(96)	176	(167)	190	(180)	133	(127)	115	(110)	173	(164)
Total Project Cost ($/kW)	1876	(1446)	2194	(1854)	3430	(2598)	3626	(2674)	3710	(2674)	2202	(1730)
Total Project Cost ($/kWh)	469	(362)	549	(464)	858	(650)	907	(669)	928	(669)	551	(433)
O&M Fixed ($/kW-yr)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)
System RTE	0.86		0.72		0.675	(0.7)	0.75		0.83		0.72	
Annual RTE Degradation Factor	0.50%		5.40%		0.40%		0.34%		0.35%		1.50%	
Response Time (limited by PCS)	1 s		1 s		1 s		1 s		1 s		1 s	
Cycles at 80% DoD	3500		900		10,000		4000		3500		3500	
Life (Years)	10		2.6	(3)	15		13.5		12.5		10	
MRL	9	(10)	9	(10)	8	(9)	9	(10)	7	(9)	6	(8)
TRL	8	(9)	8	(9)	7	(8)	8	(9)	6	(8)	5	(7)

2.2 Total Costing - current and projected future

The information presented in Table 2.2 further demonstrates that the lead-acid is not only a mature technology, but also one of the cheapest battery storage option of the all the technologies presented. Its energy and power capital costs range from 200 to 400 ($/kWh) and 300 to 600 ($/kW), compared to the values presented for the other technologies. It also obvious that the ZEBRA presents cost effective power and energy solutions. Though the lead-acid battery is mature and presents a cheap energy storage option, it produces toxic remains, which has a negative environmental influence. Furthermore, the NiCd, VRB and PSB technologies are also toxic and they have a negative environmental influence. One of the possible measures to address issue of the negative effect is by using an effective recycling system [12]. Such a measure will minimize the cumulative environmental impact.

Table 2.2 Total cost comparison of all batteries

Technology	Year	Capital Cost	BOP	PCS	C&C	O&M	Total
Sodium-sulfur	2018	$349	$13	$46	$70	$12	$490
	2025	$246	$13	$28	$67	$9	$362
Lithium-ion	2018	$174	$16	$46	$65	$11	$312
	2025	$121	$15	$34	$62	$9	$241
Lead Acid	2018	$405	$39	$136	$274	$11	$866
	2025	$343	$37	$82	$260	$9	$731
Sodium-Metal Halide	2018	$385	$14	$48	$63	$11	$521
	2025	$265	$13	$29	$60	$9	$377
Zinc-Hybrid Cathode	2018	$170	$16	$56	$111	$11	$365
	2025	$123	$15	$34	$105	$9	$287
Redox Flow	2018	$293	$13	$46	$100	$12	$464
	2025	$207	$13	$28	$95	$10	$352

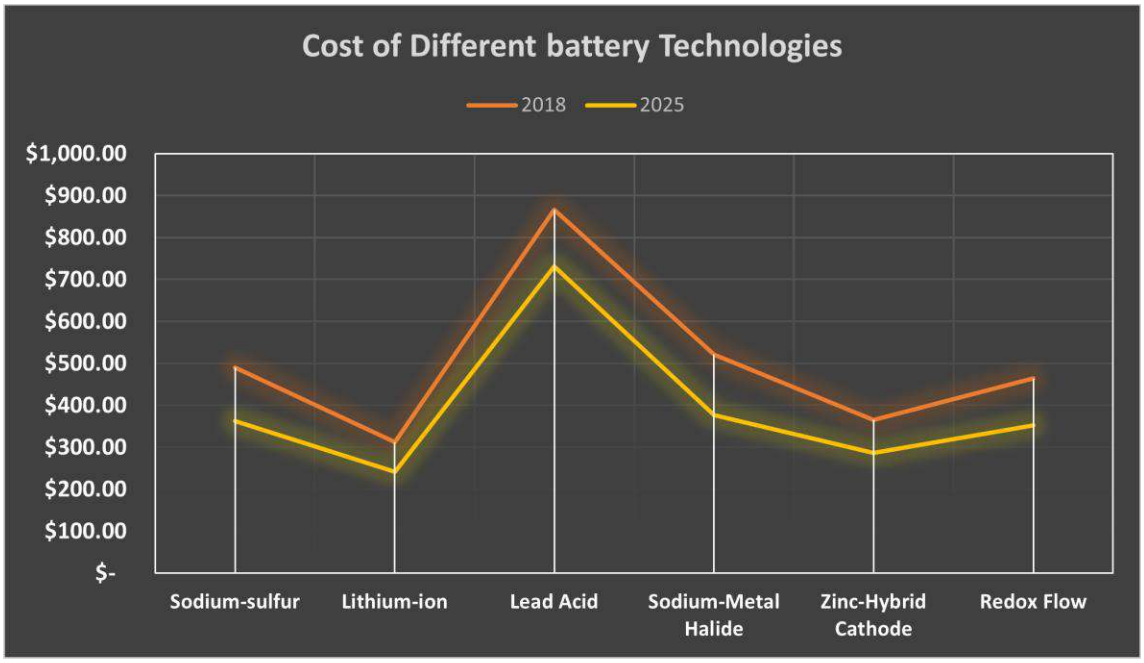


Fig. 2.3 Cost of battery technologies [13].

2.3 Lithium-Ion Batteries

By 2015, more than 500 MW of stationary lithium-ion batteries had been installed worldwide, increasing to 1629 MW by 2018 [12]. Lithium-ion batteries have been used in a variety of industries since their commercialization in the early 1990s, thanks to their high specific energy, power, and performance. The price of this chemistry is predicted to drop further because to rising demand from the electric vehicle sector and the energy storage business. As a result, it is a popular solution for big installations, with successful grid support deployments of distributed renewables up to several megawatts.

2.3.1 Capital Cost

Modules made up of an assemblage of cells, including electrodes, electrolyte, and separators, make up the fundamental components of a lithium-ion battery. A variety of modules, as well as a BMS and a PCS, make up the battery system as a whole. Between 2010 and 2017, battery prices fell by 80%, to around $200/kWh, and it is expected that during the next eight years, the price would drop to around $96/kWh. Lahiri (2017) estimated the cost of DC-Side Modules and BMS to be in the $325–$700/kWh range, keeping the range broad to account for technological variances. Aquino et al. (2017) estimated a value of $340–$450 per kWh for a 4 MW/16 MWh lithium-ion NMC system with a fully installed cost of $9.1 million to $12.8 million. They also give pricing estimates for lithium-phosphate (LFP) and lithium-titanate (LTO) systems, which range from $340 to

$590 per kWh and $500 to 850 per kWh, respectively. In Table 11, Curry (2017) and Watanabe (2017) presented estimates at the low end of the range. Some estimations, however, were based only on the battery packs. Damato (2017) calculated an installed cost of $335–$530 per kWh, which includes the PCS, grid integration and equipment, tax, fees, and G&A expenditures. The DC battery cost was 60% of the overall installation cost for a typical 4-hour scenario. The cost of a DC battery was calculated using this multiplier. Many of the cost-estimating sites discovered presented costs as overall project averages rather than cost estimates for individual battery components. The aver- age installation cost was $932/kWh, which was substantially more than Damato's (2017) estimate. One possibility is that the higher average installed costs correlate to systems that were smaller than Damato's and hence did not benefit from economies of scale reductions. LTO expenses were not taken into account for this project. As a consequence of the dramatic reduction in lithium-ion battery costs over the previous decade, we did not utilize the high-end numbers in our DC battery system cost calculation. Costs before to 2016 were ignored, and costs for 2016 and 2017 were multiplied by 0.95 and 0.952, respectively, to account for a 5% decline in cost per year. While 5% may appear to be a little percentage, it is reasonable since just the lowest end of the cost range found in the literature was taken into account. The average price per kWh for these storage DC battery packs was $296. A study of EV battery pack cost was done to compare the DC battery cost for grid-scale storage with reported costs for EV battery packs (Table 12.). On average, EV battery pack unit energy prices were 10% less than grid-scale storage costs. The cost of an EV pack was increased by 1.1 to represent a 10% increase in cost for containerization of the packs used in storage applications. This assumption is based on a breakdown of expenses, such as labor, material, and overhead, into their separate components. Only expenditures for the years 2016–2018 were taken into account, and the costs for 2016 and 2017 were multiplied by 0.95 and 0.952, respectively. The analysis was deleted from the EV packs with the three lowest prices. The updated EV pack costs averaged 256 cents per kilowatt-hour. The weighted average cost of storage and adjusted EV batteries was $271 per kWh. The cost of a lithium-ion battery system in 2018 was projected to be $469 per kWh, based on PCS, BOP, and C&C expenses.

2.3.2 Fixed and Variable O&M Costs and Performance Metrics

Lithium-ion devices typically have a 10-year useable life and require considerable maintenance every 5 to 8 years to be functioning. For their 4 MW/16 MWh NMC system, Aquino et al. (2017a) estimates the fixed O&M cost to be in the range of $6–$14/kW-yr, and the variable cost to be $0.0003/kWh. Lahiri (2017) estimates fixed O&M costs in the range of $150–$400/kW, as well as significant maintenance costs in the region of $150–$400/kW. This analysis employed a fixed O&M cost of $10/kW-yr and a variable O&M cost of $0.0003/kWh for all battery technologies, with fixed O&M prices falling to $8/kW-yr by 2025.

2.3.3 Cycles, Lifespan, and Efficiency

While lithium-ion technology is the most advanced of the battery storage systems, it will continue to develop in terms of calendar life, energy density, and the number of cycles it can give. The majority of the research predicts life years to be in the range of 10–20 years; however, most of the literature estimates life years to be on the low end, implying the need for considerable maintenance and battery replacement to keep the system operating. When a 70% DoD is used, cycle estimates range from 400 to 5475 [14]. Over 1.5 years of testing at the Pacific Northwest National Laboratory (PNNL), grid-scale batteries had an AC-AC RTE of 83–87 percent, compared to 81 percent for a battery older than 5 years. While they are all distinct chemistries, they all show how RTE deteriorates with time. In this study, an RTE of 86 percent was utilized. A cycle life of 3500 at 80% DoD was also anticipated, as well as a calendar life of 10 years. All technologies were considered to have a PCS RTE of 96 percent.

2.3.4 Technology and Manufacturing Readiness Levels

Lithium-ion batteries were first commercialized in the early 1990s, with a wide range of uses and sizes. The technology has been rigorously tested across deployments of all scales up to the upper levels of both the TRL and MRL scales now that the scale of deployment has reached the level it has. Lithium-ion batteries have a TRL of 8 and an MRL of 9 as a result of this. By 2025, the figures are expected to grow to 9 and 10, respectively [15].

2.4 NiMH (nickel metal hybrid) Batteries

Lead–acid, nickel–cadmium (Ni–Cd), nickel–metal hydride (Ni–MH), and lithium ion are the most common rechargeable battery technologies. Plante' created the lead–acid battery in 1859, and it was the first rechargeable battery. Due to its low cost, it has become the most extensively used rechargeable electrochemical storage method, and it is particularly useful where battery weight is not a factor. Fundamental inventions in the field of nickel–cadmium batteries were produced by Edison and Junger at the turn of the nineteenth century; a significant aspect of these batteries was that the electrolyte did not participate in the electrochemical process, but solely served as a conducting medium. Until the early 1990s, when Ni–MH and lithium-ion systems began to pose a major threat, nickel–cadmium batteries had no meaningful competition. For numerous years, the Ni–MH rechargeable battery system, which was introduced in 1989, was the most popular rechargeable battery system [14]. Sony manufactured the first commercial secondary lithium-ion cell in 1991, and since then, numerous lithium combinations have been investigated as battery materials, and the usage of this battery has grown rapidly. In many applications, the introduction of new types of Ni–MH and lithium rechargeable batteries has expedited the replacement of portable Ni–Cd batteries, notably in northern Europe [15]. The desire for greater cell performance and higher power density without memory impairment, which may be accomplished with Ni–MH, lithium-ion, and lithium-polymer systems, has prompted this substitution [16]. The hazardous qualities of cadmium are another key factor in the replacement of Ni–Cd batteries. Metals such as lanthanum, neodymium, and cobalt are used in the new battery technologies, which are thought to have a lesser environmental effect. The new batteries, on the other hand, include metals for which there are few toxicological or Eco toxicological data, thus their use should be reviewed to see if they may cause other environmental issues [17].

2.4.1 General characteristics

Alkaline rechargeable batteries, which comprise nickel–cadmium and nickel–iron, include NiMH and NiZn batteries. Key advantages of both NiMH and NiZn battery chemistries are as follows: 1. Cells can be cylindrical or prismatic, and cell sizes can be varied. 2. Maintenance free, 3. Materials that are both environmentally friendly and recyclable. The specific energy of Ni-based battery chemistries is good (see Figure 2.4): 50–110Wh/kg for NiMH and 70–110Wh/kg for NiZn. NiMH has dominated HEV applications to date due to superior overall performance, environmentally friendly nature, and, most importantly, safety aspects when compared to other modern battery chemistries [18]. Advanced battery chemistries intended for HEV applications must first compete on performance, then on energy and cost. As such, NiMH HEV batteries demonstrate: 1. High

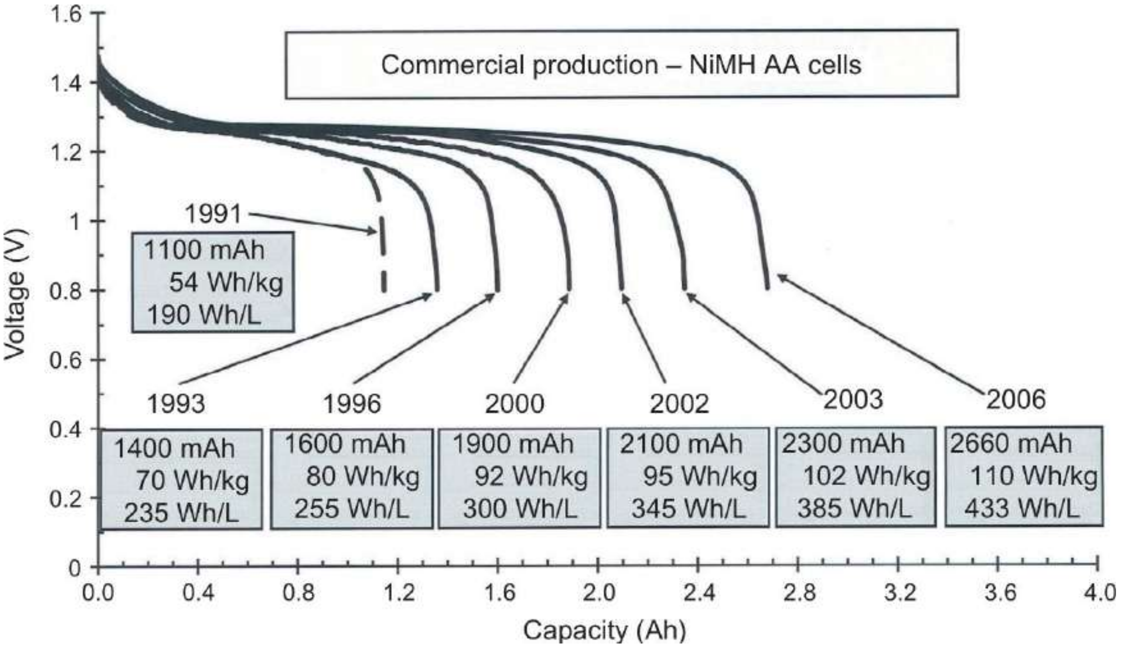


Fig. 2.4 Evolution of specific energy for NiMH cylindrical AA-size batteries [19].

power: Commercial HEVs with NiMH batteries have a specific power of 1500 W/kg [20]. 2. Packaging flexibility: HEV NiMH batteries come in cylindrical and prismatic shapes and can function at up to 320 V. 3. Long life (>1000 cycles at 100% depth of discharge (DOD) to over 1,000,000 cycles at 10% DOD) [19].

2.4.2 Chemistry and Construction of Nickel–Metal Hydride Batteries

The chemistries of Ni–MH cells must be understood in order to build an acceptable battery recycling method. A positive nickel electrode, a plastic separator, a negative metal hydride electrode, and an alkaline electrolyte, which is a concentrated potassium hydroxide solution with additional minor elements to improve the cell's working properties, are the four basic components of this battery type. The electrolyte doesn't participate in the electrochemical process since the active components are insoluble in it [21], [22]. The nickel electrode is usually made out of a porous nickel substrate soaked with nickel hydroxide, which is the principal active ingredient. The substrate functions as a mechanical support, a porous electrode, and a current collector for the active material. Small concentrations of cobalt, calcium, and zinc increase the electrode's properties, particularly the material's efficiency and electrical conductivity. The negative electrode's active material is a hydrogen storage alloy that can absorb 1,000 times its own volume of hydrogen [23]. The alloy and a conducting agent are glued into a nickel or nickel-plated steel substrate, which serves as a conductor, current collector, and physical support for the active material. For battery applications, two types of metallic alloys have been found. These are alloys containing primarily titanium and zirconium, known as AB2 alloys, and alloys containing rare-earth element (REE) alloys, known as mischmetals, with A 14 La, Nd, Ce, Pr, and B 14 Ni, Co, Mn, Al, as well as alloys containing primarily rare-earth element (REE) alloys, known as AB5 alloys, with A 14 Ti, Zr, and B 14 Ni [24]. A feature of battery recycling is that the component composition changes often, depending on the manufacturer and the time/date of manufacturing. Metal recycling is becoming increasingly important to address supply issues, since primary metal mining continues to be in high demand. Although tens of thousands of tons of REE-based hydrogen storage alloys for Ni–MH batteries are manufactured each year, the amount of nickel required to build Ni–MH batteries reached 50000–70000 tons in 2002. The utilization of recycled materials from these batteries can help to reduce the demand for virgin metal mining [25].

2.4.3 Capital Cost

In terms of final battery pack production pricing, NiMH is less than half the price of a lithium battery, and in terms of product development, it is less than seventy percent the expense of a lithium battery. Despite the fact that NiMH has several regulatory and other development hurdles ahead of it, it is still far less expensive than lithium. The progress of EV, PHEV, and HEV applications continues to be fueled by lower costs for new battery chemistries. Because of the high expense of batteries in PHEV and EV applications, most automakers are focusing more on HEVs, which have batteries that are just 5% the size of an EV battery. The goal of lowering battery costs to $150 per kWh is still being pursued with vigour. Regardless of chemistry, materials are the primary driver of battery costs. To further lower expenses, significant development initiatives are necessary. When they were first released, prototype NiMH batteries cost more than $1500 per kWh. To cut costs, a significant investment was made. Transportation NiMH costs have fallen below $800/kWh as volume manufacturing and material performance have improved, while high-volume NiMH consumer cell costs have already approached $200/kWh. The key achievements in NiMH that have allowed this significant cost reduction include: 1.Nickel hydroxide at a low price: The cost of spherical nickel hydroxide has been decreased by 30%. This has been accomplished through the introduction of new low-cost suppliers and the development of lower-cost production procedures. 2.By replacing pure nickel substrates in the negative electrode with copper- and nickel-plated steel, cell capacity and power were enhanced by 50% while costs were reduced. 3.Low-cost MH materials: Material processing improvements, new suppliers, low-cost raw materials, and improved specific capacity MH materials have all contributed to lower battery costs. MH alloys' hydrogen storage capacity (from 320 to 450 mAh/g) and nickel hydroxide usage (from 240 to >280 mAh/g) are still being researched and developed [26].

2.4.4 Rate capability

NiMH and NiZn have nominal voltages of 1.2 V and 1.6 V, respectively, with 1.0 V being the end-of-discharge cutoff in both chemistries. High-power cylindrical cells may achieve voltage profiles with a discharge rate of up to 10 °C. Cell shape and size, N/P ratio, discharge current, cutoff voltage, and temperature are all elements that affect a battery's capacity and rate capability. Temperatures between 0 and 40 °C typically provide the optimum performance for Ni-based batteries. Figure 2.5 shows the room temperature discharge curves at different speeds. Temperature performance is critical in electric vehicle (EV) applications since the cars can be subjected to temperatures as high as 50 degrees Celsius or as low as 0 degrees Celsius in places with either hot or cold climates. Oxygen evolution occurs at significantly earlier stages of charge at higher temperatures, resulting in less charge uptake in the positive electrode and poorer capacity. The electrolyte resistance rises at low temperatures, lowering the discharge performance of the batteries [27].

2.4.5 Cycle life

In automotive applications, the emphasis on power (HEV) vs energy (PHEV/EV) has a significant impact on total battery life and the testing process used to calculate cycle life. Differences in the DOD (80% for PHEV/EV vs. 2–10% for HEV) may and do have a major impact on total cycle life. The key of PHEV/EV batteries is energy density, and the measured parameter is miles traveled in pure charge-depleting (EV) mode. The dynamic stress testing (DST) driving profile, which employs a variable current/time discharge profile to replicate real-world driving circumstances, is used in pure EV mileage-mode cycle-life testing. During most PHEV/EV cycle-life testing, the battery will be used at

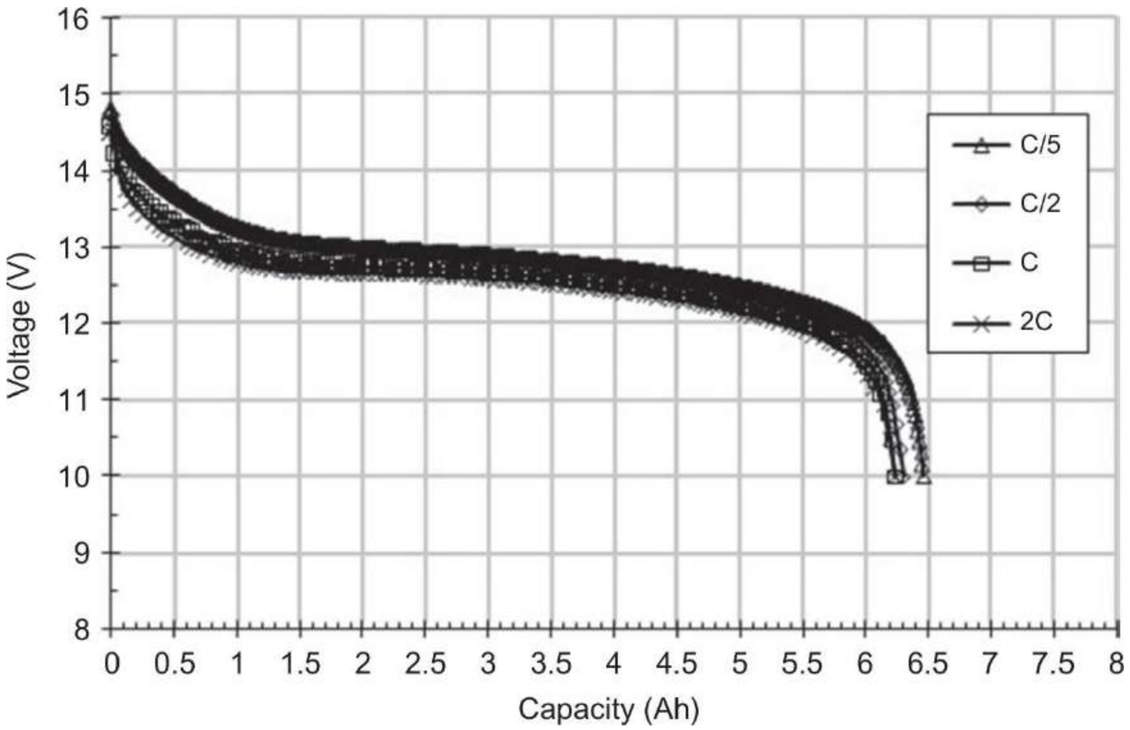


Fig. 2.5 Voltage–capacity profiles for HEV NiMH cylindrical batteries at different rates on continuous discharge [13].

80% of its rated capacity. These batteries may typically last between 600 and 1200 cycles see Figure 2.6. Unlike EV batteries, HEV batteries place a premium on power and are often evaluated using a high-current pulse profile with a 2–10% state-of-charge (SOC) fluctuation around a 50–70% SOC state. Under these conditions, HEV batteries can achieve over 300,000 see Figure 2.6 cycles, which corresponds to the vehicle's estimated life after approximately 150,000 kilometers, according to United States Advanced Battery Consortium (USABC) test methods [13].

2.4.6 Charge retention/shelf life

In Ni-based battery chemistries, the separator, positive, and negative electrodes all have a role in minimizing self-discharge. Nickel hydroxide is an electrically insulating substance in and of itself. As a result, chemicals (most notably cobalt oxide) are used to form a conductive network between the particles. However, owing to self-discharge, the SOC of a NiMH battery declines during storage and is strongly dependent on temperature. The cobalt-conductive network in the positive electrode is vulnerable to deterioration due to self-discharge losses. The cobalt-conductive network begins to break down when the cell loses its charge, with the CoOOH converted to Co 2+(oxide) or Co

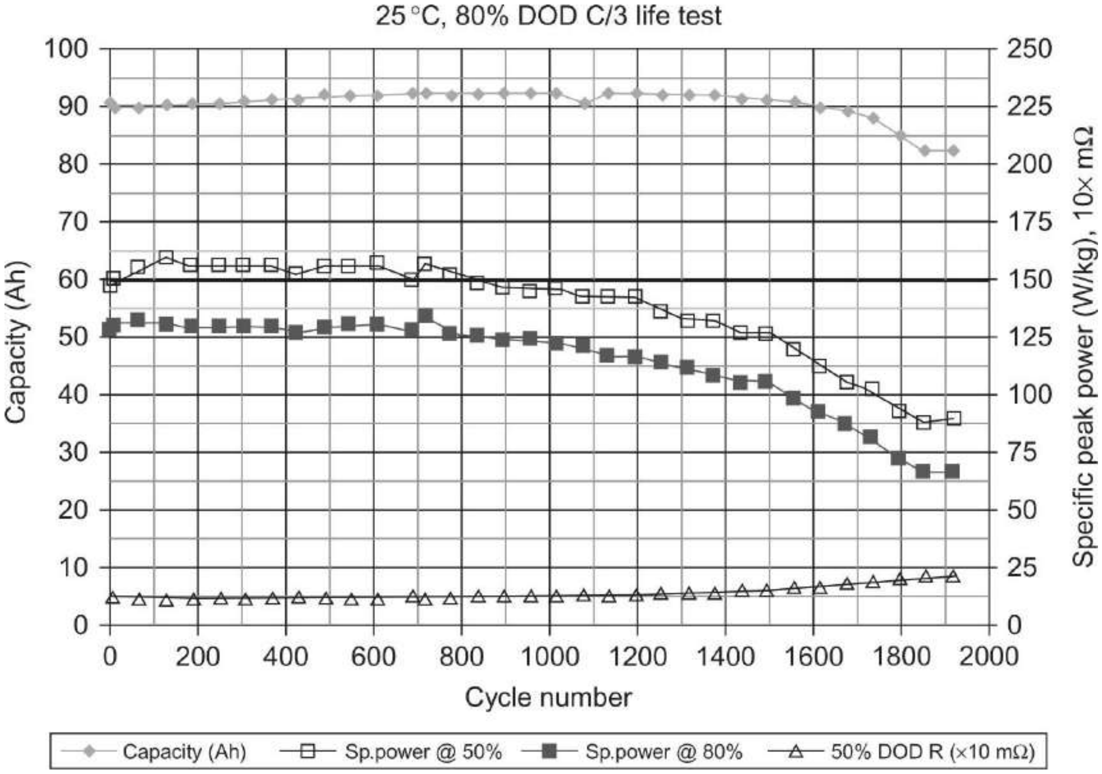


Fig. 2.6 Cycle life of cylindrical HEV NiMH battery [13].

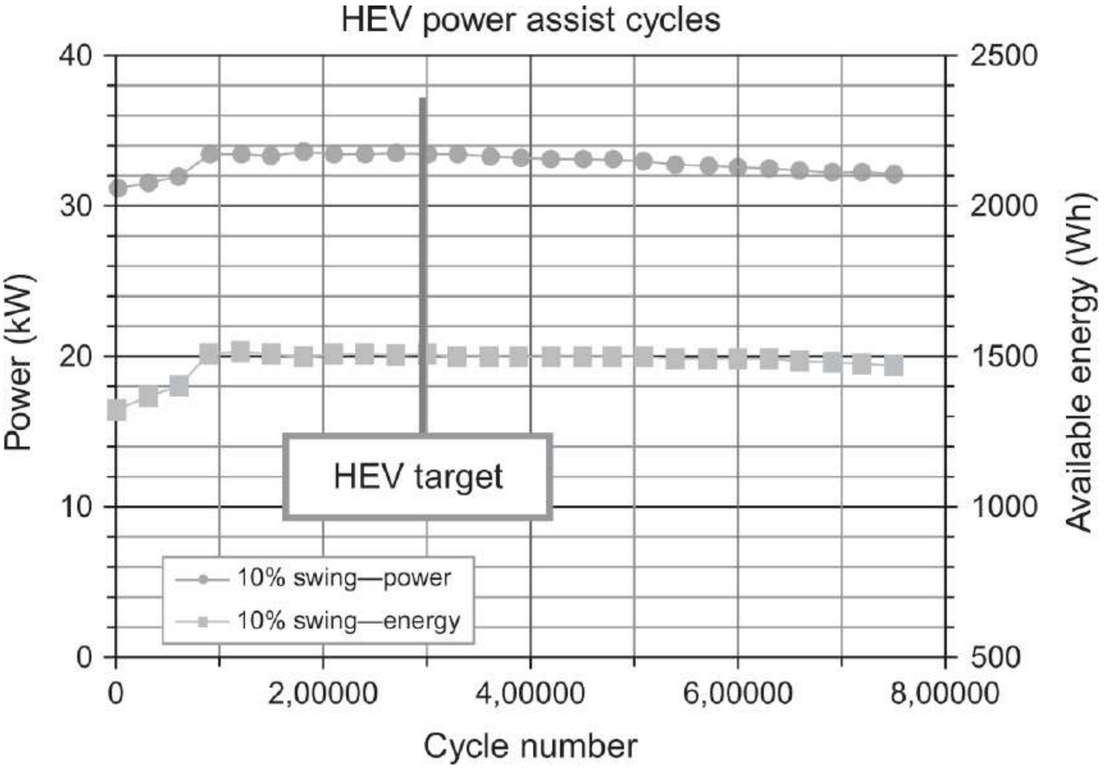


Fig. 2.7 Cycle life of large prismatic NiMH battery [13].

metal and able to travel elsewhere in the cell. The self-discharge mechanisms are influenced by the quality of the nickel hydroxide material, the usage of encapsulated nickel hydroxides, and residual contaminants such as nitrates and carbonates. As a result, two techniques for combating cobalt breakdown have been devised. To prevent the conductive network from breaking down, one way calls for larger quantities of cobalt compounds in the positive electrode paste. Another method that is becoming increasingly common is the use of "cobalt encapsulated" active compounds. The manufacturer’s nickel hydroxide coated with cobalt hydroxide has showed that the cobalt is in a more stable condition [28]. Cobalt encapsulation has also been shown to improve utilization, high-rate discharge performance, and self-discharge Kanagawa, 1998. The nickel hydroxide cathode’s intrinsic oxygen stability further aids self-discharge.

Although the nickel hydroxide cathode contains cobalt and zinc additions to limit oxygen evolution, contaminants like as iron and copper may work against this effort, and corrosion species from the anode may also increase this self-discharge process. As a result, the cell producer is especially concerned with selecting anode materials with low corrosion rates for low self-discharge NiMH consumer cells offered in the charged state [13].

2.5 The vehicles which used the mentioned Battery

2.5.1 GM EV1

The GM EV1 is the model. At least, such was the case. To make sure no one accuses us of burying the lead, GM smashed all but a few of the 1,117 EV1s it made [29]. GM also bricked 99 percent of the ones it didn’t crush, with one ending up to the National Museum of American History in Washington, DC. The remaining EV1s were mostly donated to colleges and museums [30].

The EV1 was a lot of things at the same time. Californian officials have mandated that the manufacturing and sale of zero-emission automobiles be increased. Based on what it learnt winning the World Solar Challenge for solar-powered automobiles, a production version of an extremely interesting concept car (named the Impact; that’s it in the photo above) developed for GM by a firm called Aero Vironment whose typical business is producing military aerial drones And it’s the first venture into mass-market electric automobiles since we all ditched our top hats [31].

Especially because it only had 137 horsepower. Especially given the fact that it was a 1990s electric automobile. It took roughly eight seconds to accelerate from 0 to 60 mph, which may not seem like much these days, but it’s enough to beat off current 3 Series and T5-powered Volvos [32]. In a standing-start drag race, we've seen film of the EV1 dumping an MX-5 and scooping up a 300ZX. GM removed the speed limitation from a prototype and it hit 183.8 mph, despite the fact that standard production EV1s were limited to 80 mph from the factory. With 137bhp, top whack is 165mph, according to our calculations. This tells us two things: 165 mph is still a lot of speed for a car with only 137 horsepower, and GM's engineers cranked up the wick for the maximum speed run [33]. This remarkable acceleration is mostly due to a drag coefficient of 0.19, which the Volkswagen XL1 would only narrowly beat by 0.01 almost a decade later, and which puts it miles ahead of almost any automobile you've ever seen in person [35].

Fig. 2.8 External look of Gm EV1 [34].

There's just one right now: The Chevy Bolt, a compact electric hatchback that can only be driven in left-hand drive. It is sold in the United States, Canada, South Korea, and Norway, but now that Opel is owned by Peugeot, European deliveries are a little more difficult [36].

This year, an electric SUV with a Cadillac label is planned, as well as the return of Hummer – yes, that Hummer – as a fully electric GM business. Is it really necessary to point out the irony?

General Motors "aspires to eradicate tailpipe pollution from new light-duty cars by 2035," a goal it will achieve provided the tides continue to move in the same direction they have, but not if they don't. President Biden recently issued a series of executive directives emphasizing the importance of combating climate change [37].

2.5.1.1 *Used Technologies*

To be honest, some very spectacular stuff Like magnesium-alloy wheels, a la Lancia or a racing Alfa from the glory days. Even with 26 hefty lead-acid batteries, it was fashioned from aluminum and composites to reduce the weight down to just 1360kg [38].

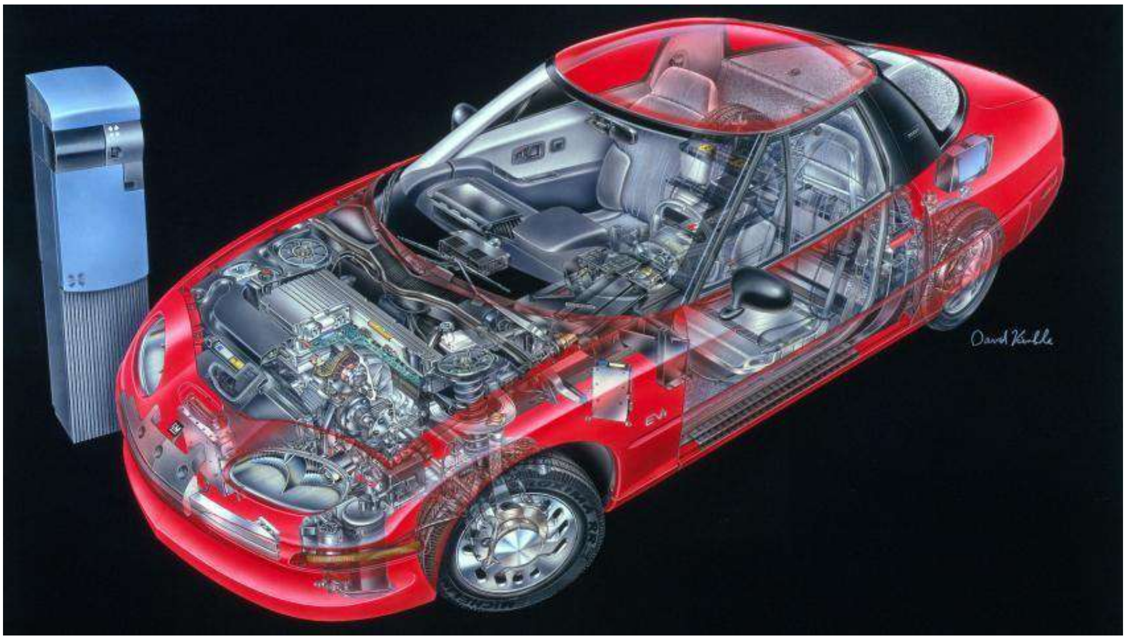


Fig. 2.9 Internal structure of Gm EV1 [39].

You could get 100 miles from a full charge with the early versions if you pushed the accelerator all the way down, but if you drove like we do, you'd be looking at half that. Later EV1s had a more powerful battery, with a range of 120 to 140 miles. This was made possible by a significant advancement in Nickel-Metal Hydride batteries made by Ovonic Battery Company, which was owned by GM at the time. Nickel Metal Hydride is a type of battery that is still used in hybrid autos today [40].

It also utilized inductive charging panels rather of the different connectors and pins that we have to deal with nowadays. So forget about CHAdeMO, CCS, and supercharging; simply slide the paddle down the front of the car - every production EV in America had the same type – and Robert is your father's brother [41].

2.5.1.2 *Apparent cost*

The EV1 initiative is said to have cost between 350 and 500 million freedom francs, none of which were recouped. At roughly $500 per month, it wasn't exactly inexpensive for drivers to lease. The year was 1990. Yes, we mentioned lease, which will be crucial later [42].

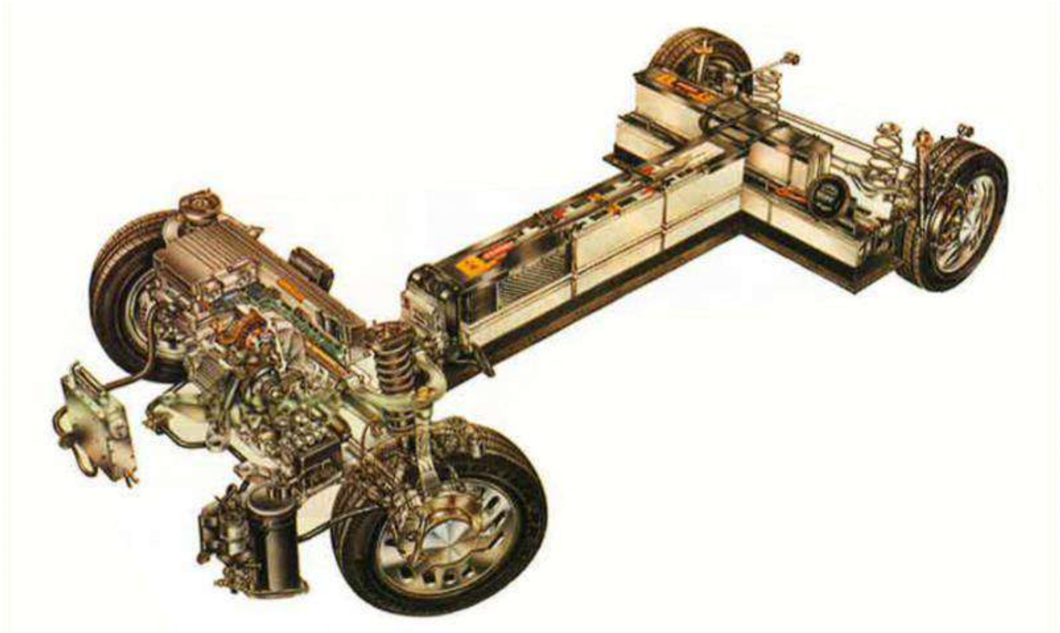


Fig. 2.10 Internal structure of Gm EV1 [43].

In the 1990s, the real sticker price was around $34,000, which translates to almost $60,000 when adjusted for inflation. That's a nice sum of money, but it's still not enough to buy a Model S. Which is obviously a different kettle of fish, but when was the last time you heard of somebody putting fish in a kettle? What a ridiculous notion [44].

2.5.1.3 *Why did it fail, and what did we learn from it?*

GM lost money on every EV1 it made and didn't see a profit for the model at any point. The aggravating thing is that GM was really rather successful at electric cars; in 1987, the Sunraycer (you know, like sunray plus racer?) won the World Solar Challenge in Australia. It also sold a fully electric car in the 1990s, more than a decade before Elon Musk would introduce the Model S and completely surprise the industry. It had interested purchasers and lessees picketing General Motors in California, attempting all they could to acquire the existing 1100-odd cars and take on responsibility for their care, giving up warranty and spare parts rights in the process. It didn't work; GM destroyed the automobiles (and, we're thinking, the protestors' spirits) nevertheless [45].

And we discovered that, in terms of EV adoption, technology, and infrastructure, we're at least a decade behind where we should be. The EV1 was, without a doubt, ahead of its time. However, this was not the case. It was a product of its day and the technology available. Electric motors were powering anything from angle grinders to milk floats, and lead-acid and even NiMH batteries had been known for decades. Aerodynamics was no longer a voodoo, and electric motors were powering everything from angle grinders to milk floats [46].

Consider what would have happened if GM had considered the long term implications of the EV1. What would we be like if we had electric cars?

2.5.1.4 cancellation

By 2002, 1,117 EV1s had been built, albeit the EV1 assembly line had been shut down by GM in 1999. GM Advanced Technology Vehicles brand manager Ken Stewart alerted lessees on February 7, 2002, that the cars will be removed off the road, contradicting a previous promise that GM would not be "pulling automobiles off the road from consumers." Drivers believed that when GM returned their vehicles under the conditions of the lease, they would be destroyed [47]. The EV1 program was formally discontinued by General Motors in late 2003, under the leadership of then-CEO Rick Wagoner. GM indicated that it would not be able to sell enough EV1s to make the vehicle economical. Furthermore, the expense of maintaining a parts supply and service infrastructure for the 15-year minimum needed by California meant that previous leases would not be extended, and all of the cars would have to be returned to GM [48].

GM received letters and deposit checks from at least 58 EV1 drivers asking lease renewals at no risk or expense to the company. According to reports, the drivers agreed to be responsible for the EV1's upkeep and repairs, and that GM would have the right to terminate the lease if costly repairs were required. On June 28, GM notoriously turned down the offer and returned the $22,000 checks; in contrast, Honda, which had taken identical moves with its EV+ program, agreed to prolong the leases of its customers [49]. GM began reclaiming the cars in November 2003; about 40 were donated to museums and educational institutions (such as Mott Community College in Flint, Michigan, and the R. E. Olds Transportation Museum in Lansing, Michigan), albeit with deactivated powertrains to prevent the cars from ever running again, but the majority were sent to car crushers to be destroyed. [50].

Despite evident public interest, GM decided to cancel and discard the electric car, according to the documentary Who Killed the Electric Car? The DVD features footage of GM EV1 team members discussing a waiting list of persons interested in leasing or owning EV1s [51].

A reporter from the Los Angeles Times sought to lease an EV1 from GM in 2003, but was told that he "was welcome to join their waiting list (a few thousand) for an undetermined amount of time, along with unidentified others, but his prospects of acquiring a car were small [52]."

Dave Barthmuss, a GM official, told The Post in March 2005 about the EV1 "This car has a fervent, devoted, and devoted fan base... At any given moment, there just weren't enough of them to create a long-term financial case for GM."

Electric cars have considerably fewer moving parts than combustion vehicles, according to critics and proponents of electric vehicles. GM dreaded the introduction of electric vehicle technology since it would cut into their valuable spare parts industry. Critics also claimed that when CARB ordered that electric vehicles make up a set proportion of all carmaker sales in response to the EV1, GM became concerned that the EV1 might attract unwelcome regulation in other states. GM, along with other manufacturers, fought CARB regulations, even going so far as to fight the agency in federal court [53].

At the time of the hearings in 2000, GM said that customers just did not demonstrate enough interest in the EV1 to satisfy the CARB mandated sales targets. Customers would only select an electric car over a gasoline car if it cost a whole $28,000 less than a similar gasoline car, according to a study commissioned by the American carmaker and Toyota. According to the study's author, Dr. Kenneth E. Train of UC Berkeley, "Toyota would have to offer the average buyer a free RAV4-EV plus a check for nearly $7,000" given a normal retail price of $21,000 for a RAV4 SUV.

The Green Car Institute and the Dohring Company automobile market research agency did an independent study commissioned by the California Electric Transportation Coalition (CalETC) and found substantially different results. "The same research procedures utilized by the car industry to find markets for its gasoline automobiles" were applied in the study. It discovered that the yearly consumer market for EVs in California is 12–18% of the new light-duty vehicle market, equating to annual sales of between 151,200 and 226,800 electric vehicles, about 10 times the number mandated by CARB. The report did point out, however, that vehicles would need to have a longer range and be marketed at pricing comparable to a conventional gasoline sedan, rather than the premium requested at the time for electric vehicles.

The Toyota-GM study's findings were questioned in light of the success of Toyota's electric RAV4-EV, which retailed for $30,000 but was sold at a loss at that price.

The manufacturers also promoted hydrogen vehicles as a preferable option to gasoline vehicles at the hearings, citing a recent federal allocation for hydrogen research as support. Many people, including members of the CARB hearing committee, were concerned that the automakers were using this as a bait-and-switch to get CARB to drop the EV mandate, and that hydrogen was not as viable an option as it was made out to be [53].

Due to automobile manufactures' lack of preparation to satisfy the ZEV mandate, CARB had already pushed back deadlines multiple times. It suggested revisions in 2001 that would give automakers credit for creating advanced-technology, partial-zero-emission vehicles like hybrid automobiles instead of battery electric vehicles. The industry, on the other hand, utilized the loosening of the restrictions to challenge the regulation as a whole [54].

CARB's method of determining whether or not a vehicle qualified as an Advanced Technology Partial ZEV (AT PZEV) used the vehicle's fuel economy as one of the standards, in addition to reduced emissions; according to federal law, states are barred from regulating fuel economy in any way. GM and Daimler-Chrysler filed suit against CARB in the US District Court for the Eastern District of California, successfully arguing that CARB's method of determining whether or not a vehicle qualified [54]. On June 11, Judge Robert E. Coyle granted a preliminary injunction against the California Air Re- sources Board, declaring the provision unlawful and halting the execution of CARB's 2001 revisions. The zero-emission requirement was decreased to at least 250 fuel cell or battery-powered cars by 2008, as part of the mandate [55]. By the end of August 2004, all leased EV-1s had been returned to their lessees, and no EV-1s remained on the road. One was on display at Walt Disney World's Epcot in Lake Buena Vista, Florida's Main Street in Motion show. Some of the old EV-1s were donated to technical colleges for dismantling and examination, never to be driven again [56].

2.5.2 Nissan Leaf

The Nissan Leaf, which debuted in Japan and the United States in late 2010, is powered by a 24 kWh lithium-ion battery pack made up of polymer cells from Automotive Energy Storage Corporation. The Leaf is categorized as a BEV since it has no internal combustion engine and is driven only by the energy stored in its lithium-ion battery. There is currently no active temperature management system in the Leaf's battery system. The

Fig. 2.11 External look of Nissan Leaf in charging mode [55].

modules that encase the cells, on the other hand, are composed of aluminum, allowing them to function as heat sinks within the battery, passively drawing heat away from the cells.

The battery pack is situated beneath the car, between the passenger and driver seats, as illustrated in Figure 2.11. Because the pack is installed exactly in the center of the vehicle, this placement has a low center of gravity. This also implies that the pack must meet IP69 standards to prevent extraneous material, like as liquid or dust, from entering. The Environmental Protection Agency (EPA) estimates the Leaf's range to be around 73 miles, with roughly 34 kWh per 100-mile energy usage, based on the US drive cycle. The Leaf's fuel efficiency was likewise rated at 99 MPGe by the EPA (miles per gallon electric equivalent).

2.5.2.1Chevrolet Volt

The Chevrolet Volt, which debuted in late 2010, is powered by a 16-kWh battery made by LG Chem. The Volt is an EREV, meaning it features a 1.4-liter gasoline engine and a 16-kWh lithium-ion battery pack. Once the battery charge has reduced to a minimal level set by the system controller, the ICE works as a generator, driving the motors. The vehicle's total range is equivalent to that of a regular ICE due to the combination

Fig. 2.12 The 24 kWh Nissan Leaf Li-ion battery pack with AESC Li-polymer cells [55].

Fig. 2.13 The 16 kWh Chevrolet Volt Li-ion battery pack with LG Chem Li-polymer cells [55].

of Li-ion battery and ICE. The Volt battery is constructed in a "T" form to fit into the transmission tunnel and fuel tank locations Figure 2.12. Because it is mounted outside of the vehicle’s cabin, it is protected against the elements to an IP69 standard. It has a low center of gravity due to its placement, and its position makes it a structural component of the vehicle chassis. To heat and cool the cells, GM employs a liquid-cooled thermal management system. A plastic "frame" separates the Li-ion cells and incorporates an aluminum heat sink plate through which the cooling liquid travels to transport heat away from the cells. The cooling loops for the battery and the ICE are separate. While the pack's total capacity is 16 kWh, the Volt is only meant to utilize roughly 10.3 kWh of it. The entire life of the system is extended by lowering the battery's useful energy. Volt's capacity has been raised to 16.5 kWh, with 10.8 kWh of useable energy in the 2013 edition. The rise, according to General Motors, is attributable to a shift in chemistry within the Li-ion cells. The EPA estimates the Volt's all-electric range to be 35 miles, with a total range of 379 miles, based on the US driving cycle. The battery's energy usage is calculated by the EPA to be 36 kWh every 100 miles. With the 2013 model, the EPA boosted the Volt's fuel efficiency rating to 99 MPGe and the all-electric range to 38 miles [55].

In November, Tesla Motors confirmed earlier reports that it will purchase LG Chem cells for a battery pack upgrade to its Roadster. The Roadster was Tesla's first model offering, with around 2,500 vehicles sold between 2008 and 2011. However, only some Roadsters (the so-called versions 2.0 and 2.5) are eligible for the upgrade, limiting the total available upgrades to about 2,000 vehicles. In addition to a larger capacity battery pack at around 70 kWh shown in fig.2.13, the upgrade also includes an improved aerodynamic package and low rolling resistance tires which will reduce drag and increase efficiency. All of these upgrades, as well as labor and transport to a service center, will cost the customer $29,000. One key factor about the supply agreement is the cell format that Tesla will be using for the upgraded Roadster. Tesla has famously lauded cylindrical cells, and both its CEO and CTO confirmed that future cylindrical cells may increase about 10% in height and width from the existing 18650 format. On the other hand, LG Chem has exclusively supplied large format pouch cells like those found in the Chevrolet Volt for electric vehicles, although the company offers cylindrical and prismatic cells, as well. While the format remains unconfirmed, in the likely case Tesla will use LG Chem's cylindrical 18650 cells. However, Tesla has recently shaken up conventional wisdom about its battery technology switching to NMC cathodes for most of its stationary products and making use of silicon anodes in its premium vehicles [57].

2.6 Most usable Batteries in the Latest Electric Vehicle System

Lithium-ion batteries are used in the majority of today's PHEVs and EVs, albeit the chemistry is typically different from that of consumer electronics batteries. Research and development is continuing to lower their relatively expensive cost, increase their usable life, and solve overheating safety issues [58].

2.6.1 Lithium Ion Battery Technology

Lithium ion batteries are the dominant power source in portable devices, have begun to penetrate the electric car sector, and are about to reach the utility market for grid-energy storage [59]. Depending on the application, trade-offs between different performance criteria like as energy, power, cycle life, cost, safety, and environmental effect are frequently required, and these trade-offs are typically connected to severe materials chemistry difficulties [60]. Insertion-reaction electrodes and organic liquid electrolytes are used in today's lithium ion battery technologies. New electrode materials based on both insertion and dominantly conversion reactions, as well as solid electrolytes and lithium metal anodes, are being studied vigorously with the goal of increasing the energy density or optimizing other performance characteristics. This article gives an overview of lithium ion technology, starting with the current state and on to the future difficulties and opportunities [61]. Given the tremendous hurdles that several of the techniques face, the paper concludes by recommending realistic near-term tactics [62].

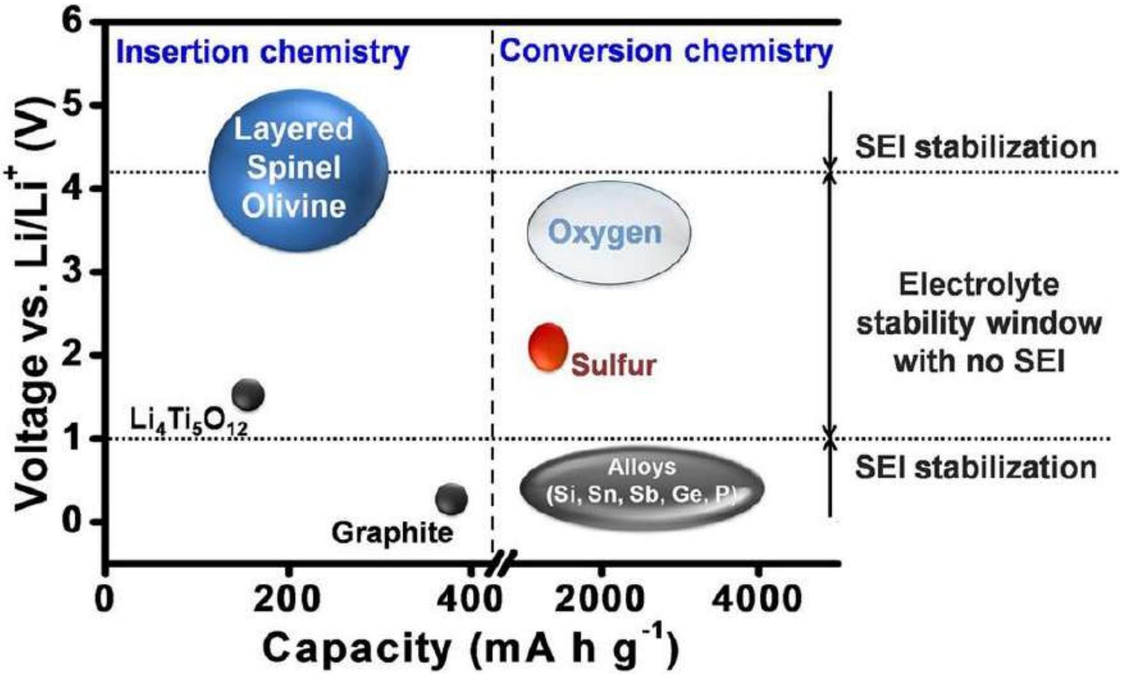


Fig. 2.14 Capacity and voltage ranges of anode and cathode materials for lithium-based batteries. The voltage stability window for the currently used liquid electrolytes in lithium ion batteries and the possibility to widen the stability window by the formation of optimal SEI layers on the electrodes are indicated [60].

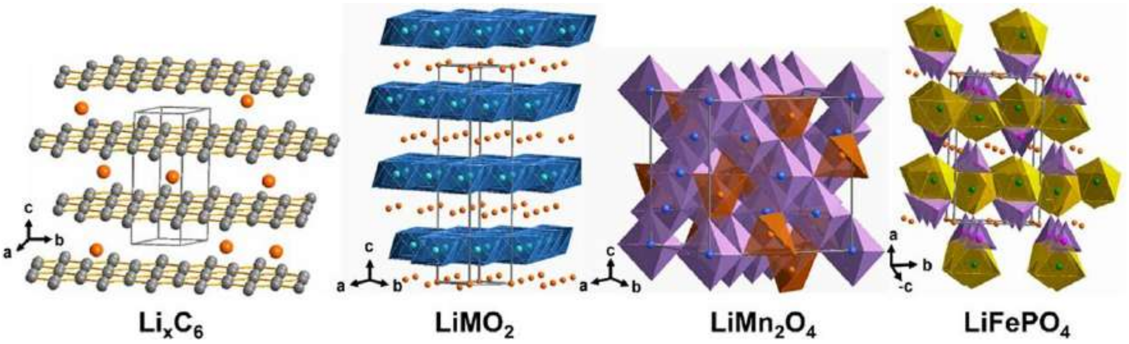


Fig. 2.15 Crystal structures of graphite LixC6, layered LiMO2 (M = Mn, Co, and Ni), spinel LiMn2O4, and olivine LiFePO4 [60].

Lithium ion batteries enabled the micro-electronics revolution and have since become the preferred power source for portable electronic gadgets. Their dominance in the portable electronics industry is due to better gravimetric and volumetric energy densities than other rechargeable technologies [63]. The increased energy density is owing to the higher working voltages of 4 V achieved by using water-free, nonaqueous electrolytes as opposed to aqueous electrolytes in other systems, which typically restrict operating voltages to less than 2V [64]. Lithium ion batteries have beginning to make inroads into the electric car sector, and they are also being aggressively sought for grid energy storage. Energy, power, charge discharge rate, cost, cycle life, safety, and environmental effect are just a few of the factors to consider while using lithium ion batteries in different applications [65]. While While energy density (driving distance between charges) is the most significant aspect for portable electronics, cost, cycle life, and safety are all critical characteristics for electric cars. For grid energy storage, however, cost, cycle life, and safety take precedence above energy density. For all three applications, a quick charge discharge rate is desirable [67]. The qualities and characteristics of the component materials utilized in the assembly of the batteries, as well as the cell engineering and system integration involved, are significantly responsible for the performance parameters mentioned above. The underlying chemistry of the materials affects their properties. Commercial lithium ion technology is now restricted to cells with gravimetric energy densities more than 250 W h per Kg and volumetric energy densities less than 650 W h per L. Volumetric energy densities are frequently more significant for portable devices and electric cars than energy densities, which are not necessary for grid storage. Around the world, there is a lot of interest in pushing energy densities to approximately 500 W h per kg and over 1,000 W h per L [68]. It will take innovation in both the component

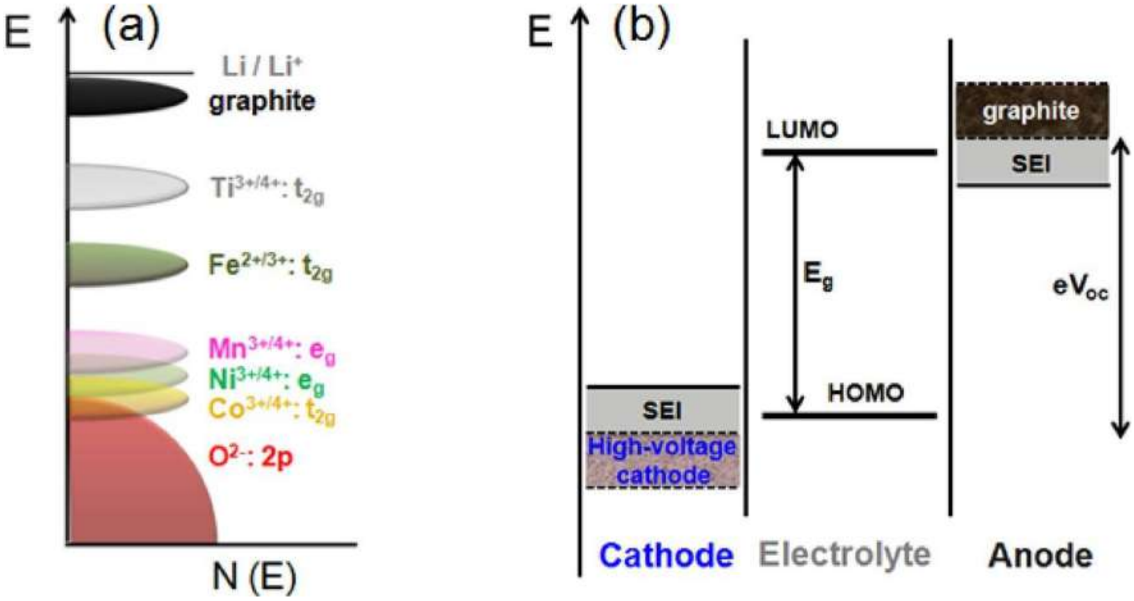


Fig. 2.16 Positions of the various redox couples relative to the top of the oxygen:2p band and (b) schematic energy levels of an anode, cathode, and electrolyte in an open circuit. The possibility to widen the stability window by the formation of optimal SEI layers on the electrodes are indicated in panel b [66]

materials utilized in the cell and the engineering involved in constructing the cells to achieve this aim [69]. The gradual gains in energy density since Sony Corporation originally announced the commercialization of lithium ion technology in 1991 are primarily attributable to engineering advances, while the component electrode materials have remained the same with minimal adjustments. The parts that follow offer an overview of the current state of technology and its future prospects, followed by conclusions [70]. Despite the restricted energy density defined by the amount of crystallographic sites accessible as well as structural and chemical instabilities at deep charge, existing lithium ion technology based on insertion reaction cathodes and anodes will continue for the foreseeable future. Conversion reaction anodes and cathodes have received a lot of attention since they have up to an order of magnitude larger capacities than insertion reaction electrodes, but their practical practicality has been questioned [71]. Recently, there has been renewed interest in using lithium metal as an anode and substituting liquid electrolytes with solid electrolytes because they can provide safer cells with greater operating voltages and charge storage capacity, but only time will tell if they are practicable [72]. Given the challenges of the alternatives (conversion-reaction electrodes, lithium metal, and solid electrolytes), a viable near-term strategy is to focus on high nickel layered oxide cathodes, liquid electrolytes compatible with and forming stable SEI on both graphite

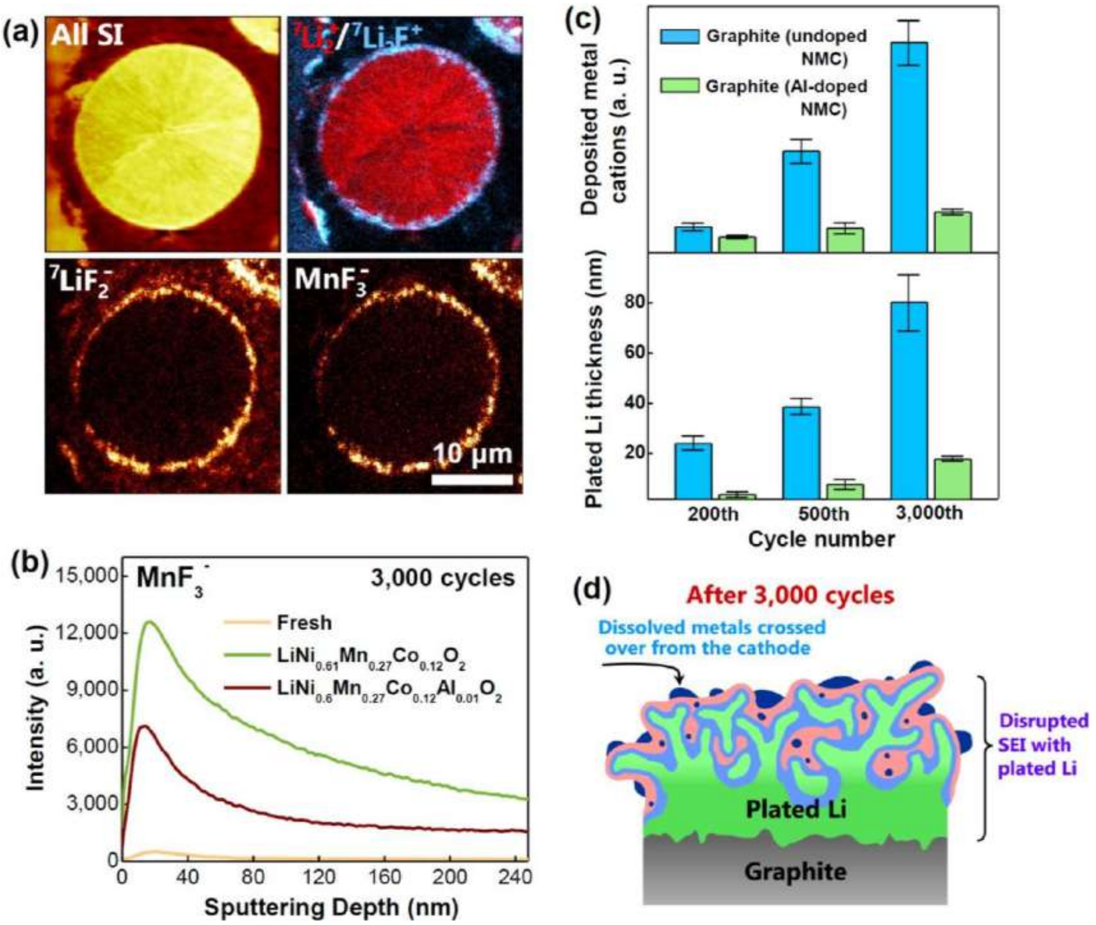


Fig. 2.17 (a) TOF-SIMS chemical mapping of the organic electrolyte decomposition layer and dissolved transition-metal layer in the form of fluorides on an NMC cathode particle. (b) Comparison after 3,000 cycles of the amounts of transition-metal dissolution, forming metal fluorides (e.g., MnF2), from an undoped and a 1 mol % Al-doped NMC cathode relative to that from a fresh electrode. (c) Comparison after 3,000 cycles of the amounts of dissolved transition metals and the calculated thickness of Li metal dendrites on graphite anodes that were paired with an undoped and a 1 mol % Al-doped NMC cathode. (d) Schematic illustrating the evolution of the SEI on graphite anode during cycling under the influence of dissolved transition-metal ion crossover from the cathode to the anode. Reproduced with permission from ref 37. Copyright 2017 American Chemical Society [59].

anode and high Ni cathodes, cell engineering innovations to fabricate thicker electrodes and reduce inactive components, and novel system integration to realize safer, long-life, affordable systems [59].

CHAPTER 3

SYSTEM DESIGN

3.1 Vehicle design

An electric vehicle can be simplify as shown in **Fig. 3.1**.

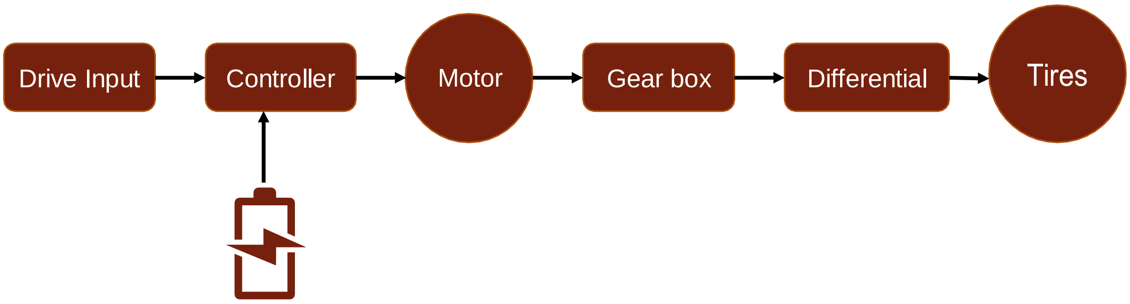


Fig. 3.1 Electric vehicle simplified block diagram

Table 3.1 EV parameters

Parameters	Value
Vehicle body	
Mass	600 kg
Wheels/axel	2
Drag	2 m^2
Air density	1.18 kg/m^3
Motor	
Type	Permanent magnet
Motor rotor inertia	gcm^2
Field resistance	100 ohm
Field inductance	1 H
Mutual inductance	0.15 H
Tyres	
Radius	0.3 m
Rated load	3000 N
Slip	10
Battery	
Capacity	50 Ah
Nominal voltage	50 V

Drive input Drive input simulates the driver of an actual vehicle. Basically, the speed, acceleration, brakes etc, are controlled with the drive input.

Controller Controller controls the battery state of charge and speed of motor along with other controlling.

Battery Battery and soc controller are part of this part.

Motor Motor is connected with the controlled circuitry and with the gear box.

Gear Differential and gear makes the gear box. The function is to change the speed (torque) of the motor.

tyres The gearbox is connected with the tyres.

The detailed simulation model is presented in **Fig. 3.2**. During the simulation of this EV model, we haven't paid extremely precise attention to the control of the drives of the vehicle since our main focus is to observe the battery performance of the vehicle. Here this simulation represents a simple EV model with interchangeable battery. The parameters of the battery is shown in **Table 3.1**.

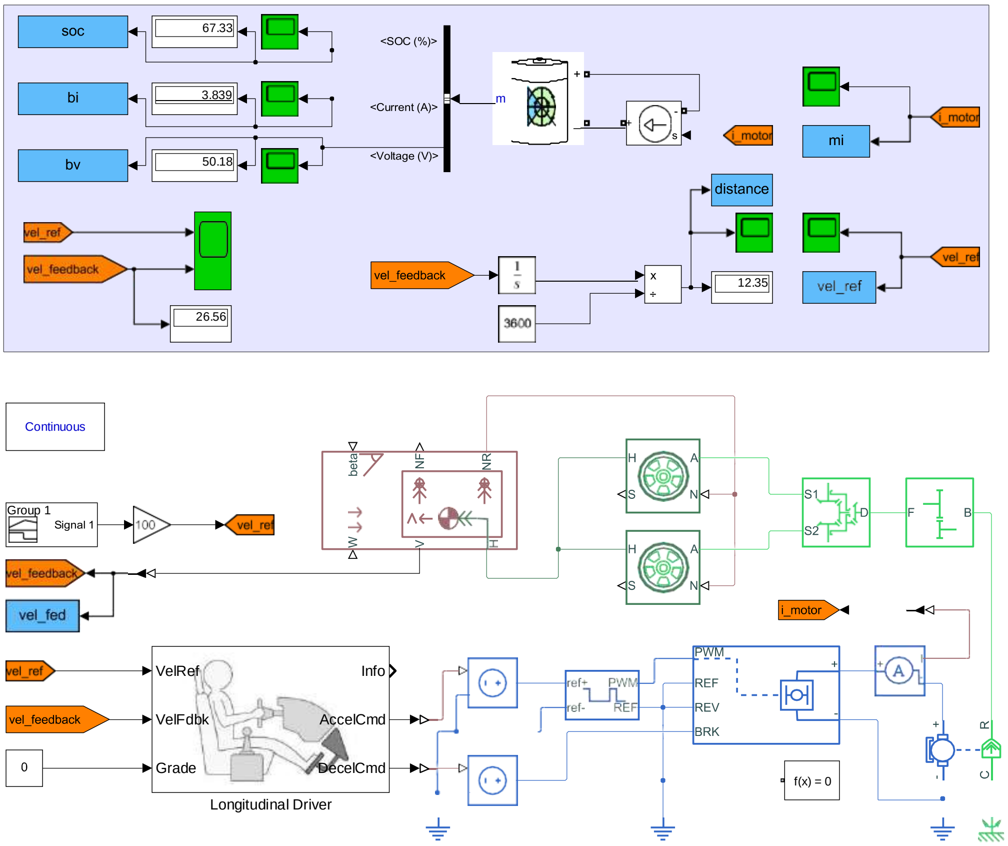


Fig. 3.2 Electric vehicle model in MATLAB Simulink

3.2 Simulation

We have simulated the EV for 1000 seconds. The velocity comparison of reference and actual is shown in **Fig. 3.3** We can see the there are very little flection between the refer-

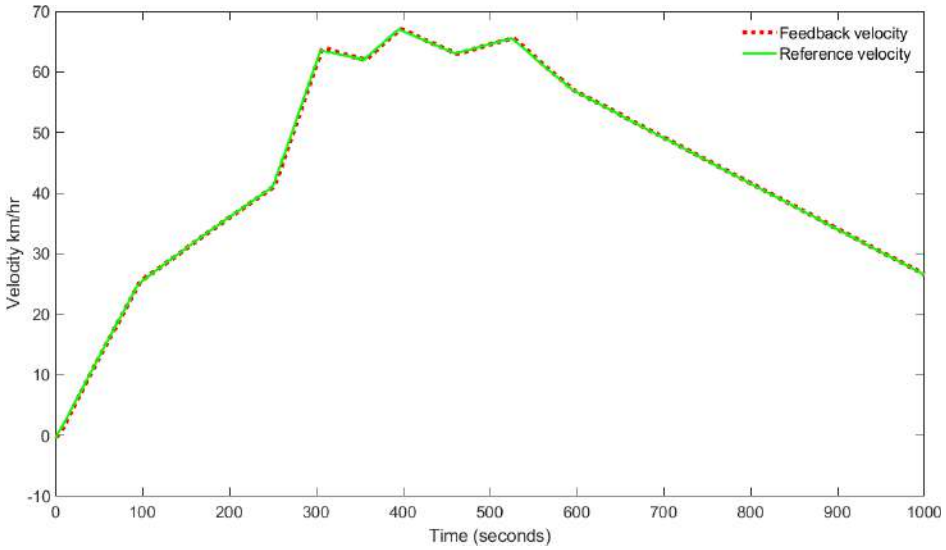


Fig. 3.3 Comparison of the reference and simulated velocity of the EV

ence and actual velocity of the EV. Hence this concludes that the controlling of the EV is ok and working perfectly. The motor current is shown in **Fig. 3.4**. From the motor current figure it is clearly seen that during acceleration of the EV the motor current drastically increases. On the other hand motor current decreases during deceleration. It can be visualized better from the figure it is clearly seen that sometimes the motor current

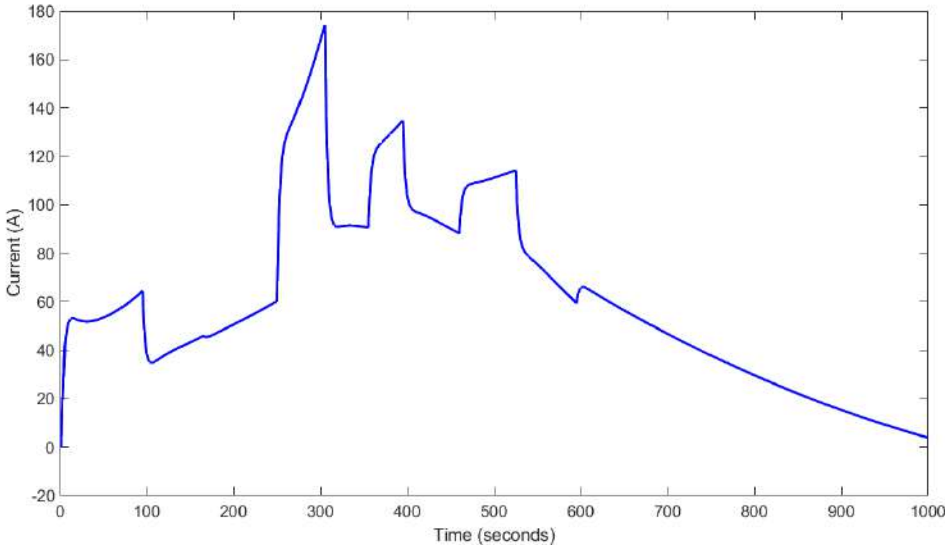


Fig. 3.4 Current flow through the motor

drastically increases and sometimes it decreases during instantly. It can be visualized better from **Fig. 3.5**. Here we can see that current rapidly increase during acceleration and decreases rapidly during deceleration. The instantaneous increase occurs during the high value of acceleration as seen around 300 seconds in the x axis. The total distance

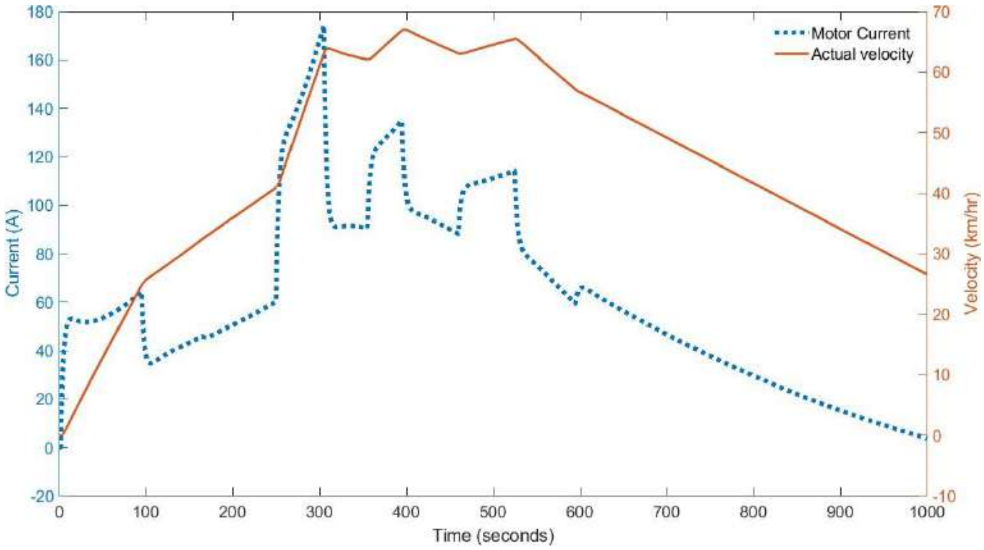


Fig. 3.5 Increase and decrease of motor current due to acceleration and deceleration of the EV

travelled during this 1000 seconds is shown in **Fig. 3.6**. The distance graph is non-linear because the velocity is constantly changing. The distance graph will be linear in case of constant velocity. State of charge of the battery is shown in **Fig. 3.7**. Battery percentage

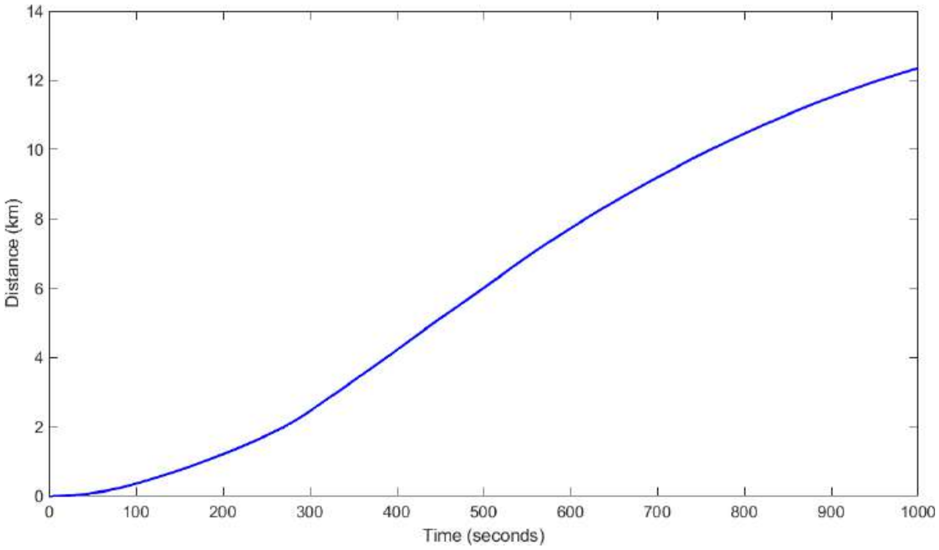


Fig. 3.6 Approximately 12.3 km distance travelled during the simulation

was 100% at the start of the simulation and it is 66% at the end of the 1000 seconds run. So, there is 34% battery consumption during the simulation. The battery consumption might look very high but it’s ok. The battery size is 50 Ah, and nominal voltage of the

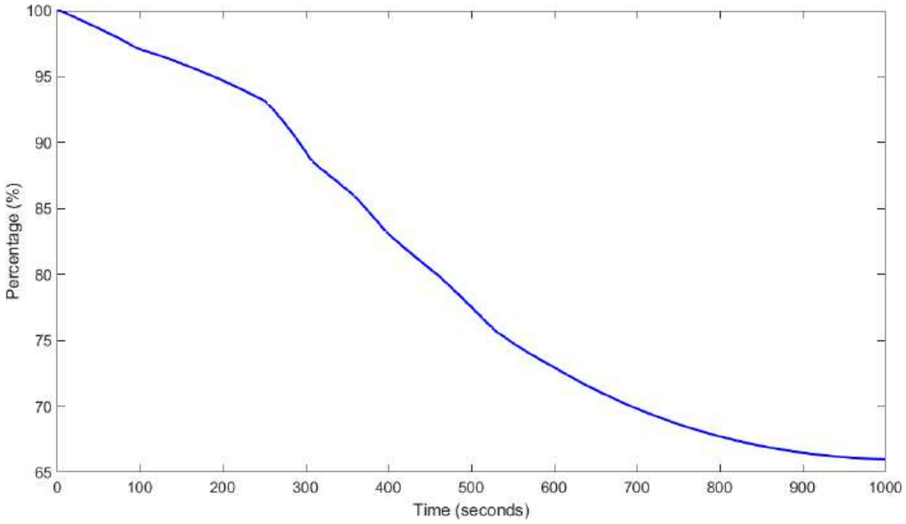


Fig. 3.7 SOC of the EV

battery is 50 V. Hence the size of the battery is -

$$50Ah \times 50V = 2500wh = 2.5kWh \tag{3.1}$$

which is not a large battery size for an electric vehicle. **Fig. 3.8** shows the battery voltage and current.

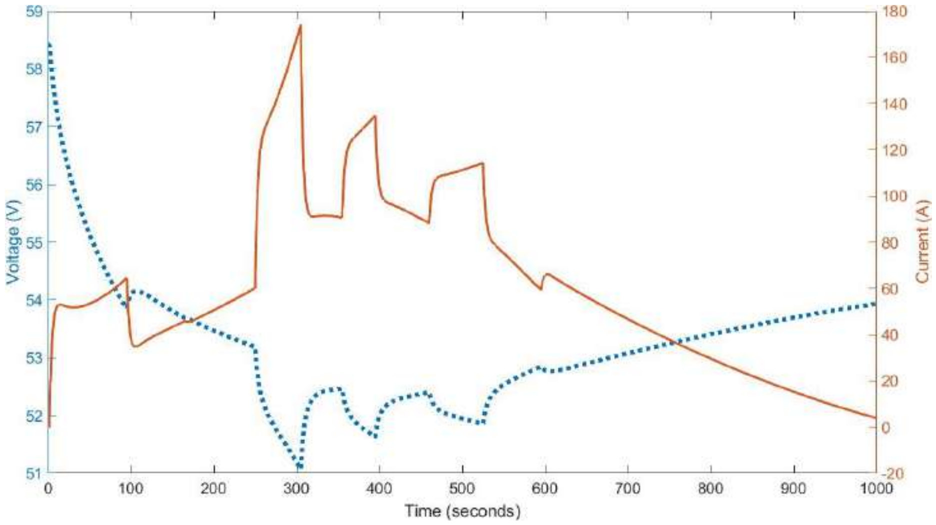


Fig. 3.8 Battery voltage and current

CHAPTER 4

RESULTS ANALYSIS

4.1 Introduction

In chapter 3 we have shown the system design and initial simulation results shows that the system is working perfectly. In this chapter, we will organize all the results from the simulation, literature review and analysis. For that, we will change the battery of the EV to lead acid, Ni-Mh and Li-ion and observe the response soc, voltage and currents of these batteries.

4.2 Result

4.2.1 Lead acid battery

SOC of lead acid after the 1000 seconds simulation is shown in **Fig. 4.1**. From the figure we notice that during this 1000 second simulation phase the battery drains around 33% and become 67%. Also we can see that at around 300 seconds the battery starts to drain faster, it's because of the rapid acceleration from that point.

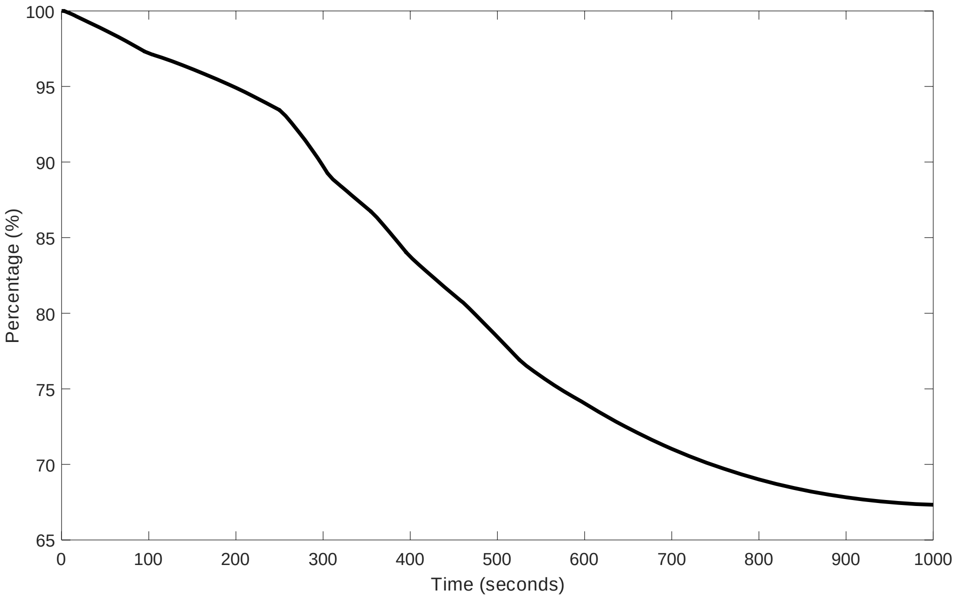


Fig. 4.1 SOC of lead acid battery

Fig. 4.2 shows the voltage and current of the lead acid battery during the simulation. we notice the maximum battery current during the acceleration. Battery current should be the same during all three batteries because of the unchanged input velocity.

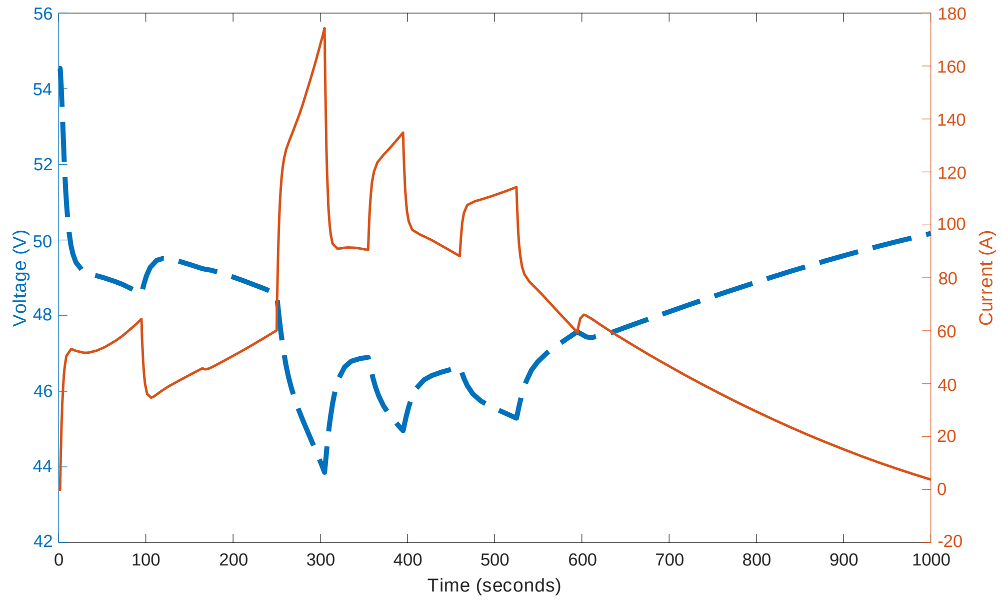


Fig. 4.2 Voltage and current of lead acid battery

4.2.2 Ni-MH battery

SOC of Ni-MH battery is depicted in **Fig. 4.3**. From the figure we notice that during this 1000 second simulation phase the battery drains around 32% and become 68%. **Fig. 4.4** shows the voltage and current of the lead acid battery during the simulation. If we notice the y axis scaling carefully we see that voltage fluctuation situation is better in Ni-MH battery compared to lead acid.

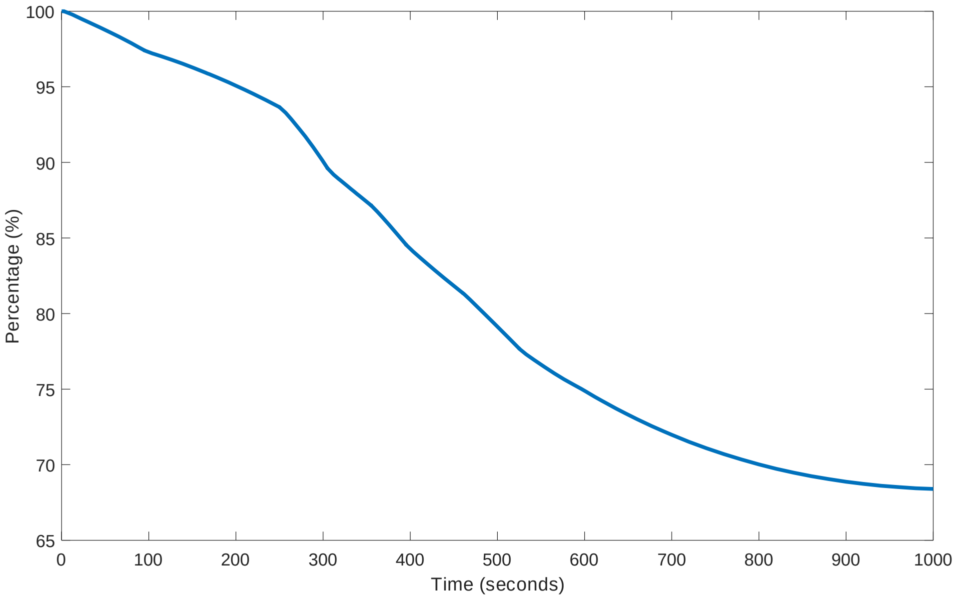


Fig. 4.3 SOC of Ni-MH battery

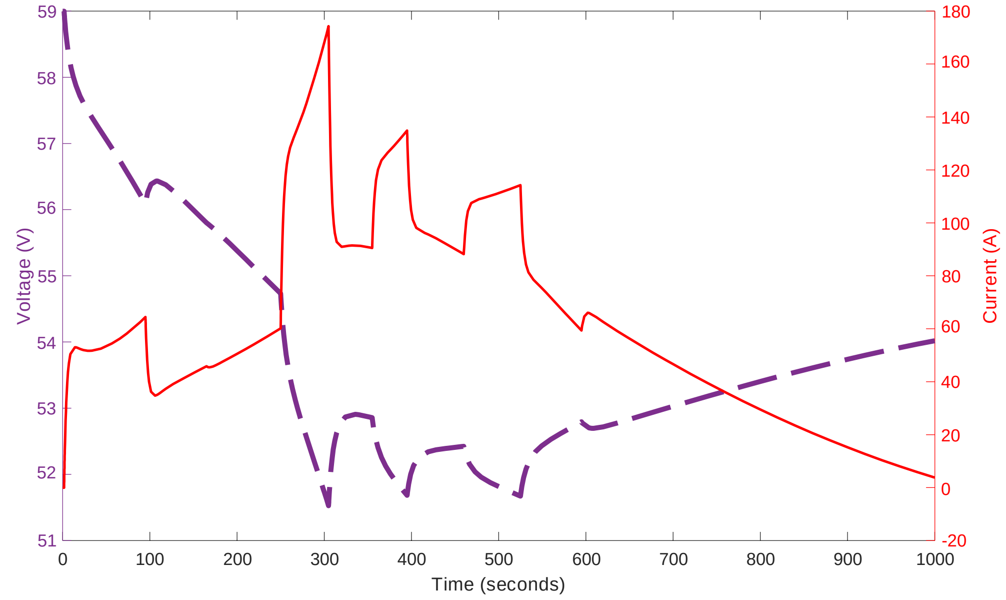


Fig. 4.4 Voltage and current of Ni-MH battery

4.2.3 Li-ion battery

SOC of Li-ion battery is shown in **Fig. 4.5**. From the figure we notice that during this 1000 second simulation phase the battery drains around 34% and become 66%. Among the three batteries Li-ion consumes more battery power compared to other two. **Fig. 4.6** shows the voltage and current of the lead acid battery during the simulation. Voltage of battery is compared to that of Ni-MH.

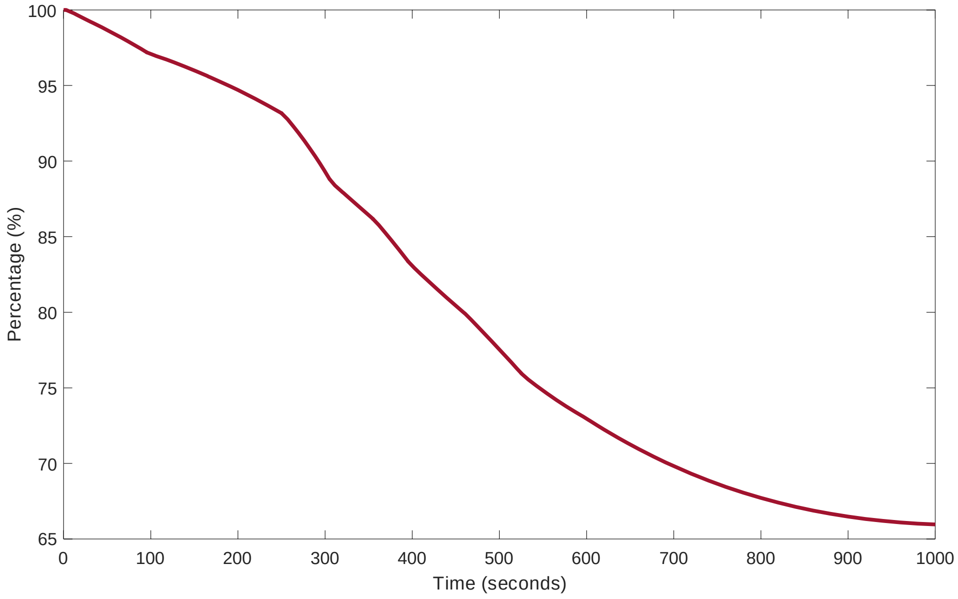


Fig. 4.5 SOC of Li-ion battery

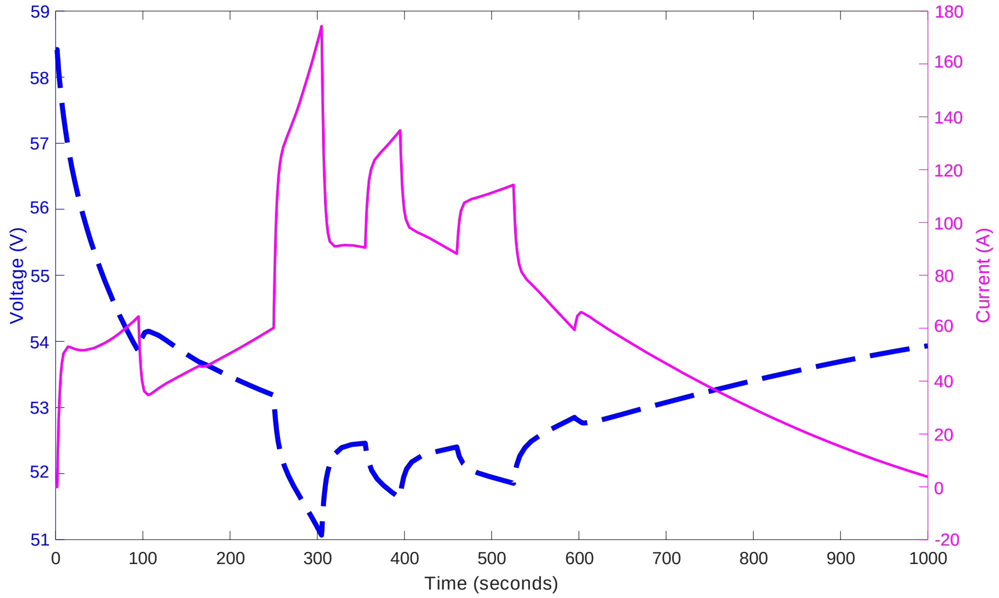


Fig. 4.6 Voltage and current of Li-ion battery

4.2.4 Comparison of the three batteries

We have compared the state of charge, voltage and current of the battery. Comparison of SOC of three batteries is shown in **Fig. 4.7**. Among the 3 three batteries, Ni-mh

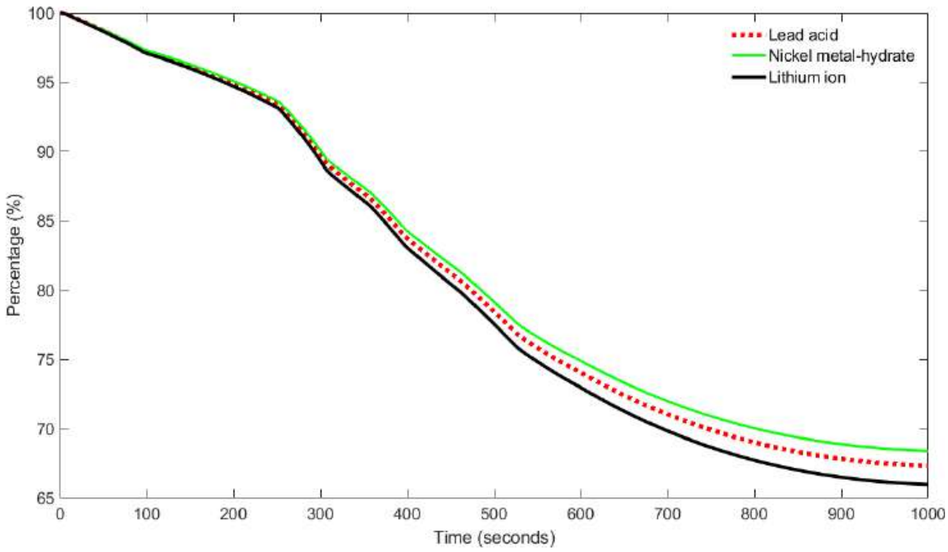


Fig. 4.7 SOC comparison

is little bit more efficient in terms of SOC. Lithium ion comes second and lead acid comes at last. Nominal voltage of the battery is shown in **Fig. 4.8**. From this figure we notice that, lead acid battery is very sensitive towards the nonlinear change of velocity. During acceleration and deceleration of vehicle the voltage fluctuation is significantly higher

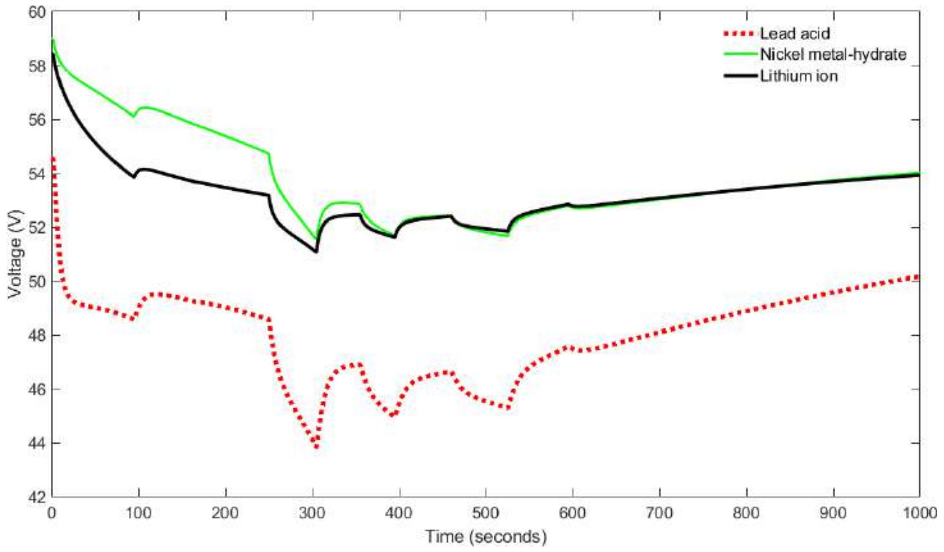


Fig. 4.8 Battery nominal voltage comparison

in lead acid battery compared to other two. Since the reference velocity of the vehicle remains the same hence battery and motor current should remain the same for all three batteries. Comparison of the battery current is shown in **Fig. 4.9**.

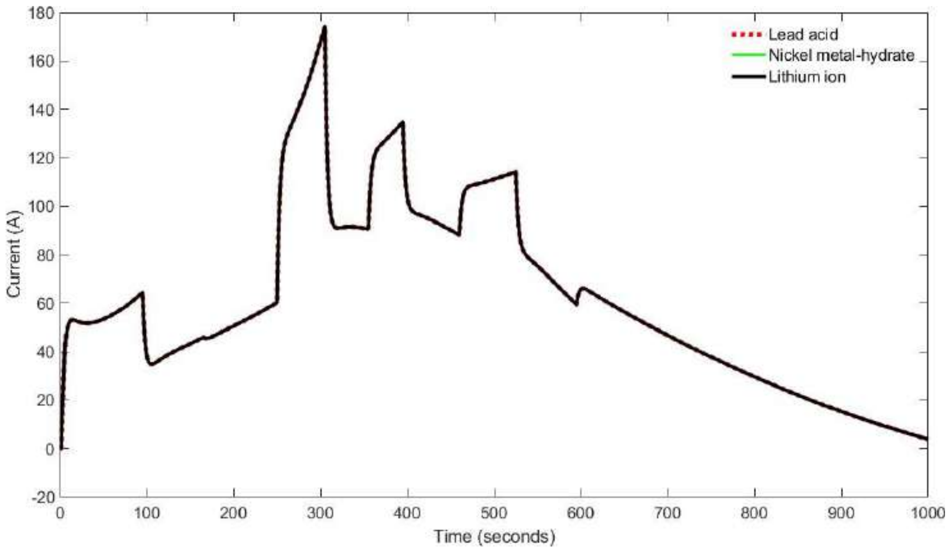


Fig. 4.9 Battery current comparison

4.3 Other battery parameters

It is not possible to show many important parameters like life cycle, specific energy of a battery in simulation. Hence we will discuss those parameters here that can't be shown in simulation.

4.3.1 Specific energy, energy density & specific power

Specific energy refers to the energy consumption time per kilo gram of a battery. The unit of specific energy is Wh/kg or kWh/kg. The simple meaning of this is - how many units of electricity per kilogram battery can provide. Energy density and specific power also refers to almost the same physical meaning of specific energy. The weight of a battery pack depends on these parameters directly. For example the weight of a Tesla models is around 2050 kg with a 85 kWh battery whose weight is 540 kg [73]. The weight of the battery is more than one fourth of the total weight of the vehicle. The noticeable thing is, lithium battery has been used in this vehicle whose specific energy is far higher than that of lead acid and nickel metal hydride. If a nickel metal hydride battery of 85 kWh was used in Tesla model S then the total weight of the vehicle would be around 2600 to 3500 kg and the battery weight would be around 1200 to 1800 kg at least. And for the case of a lead acid battery vehicle weight would be 3500 to 5000 kg and the battery weight would be 2000 to 3500 kg. The battery weight would be multiple times higher than the actual weight of the vehicle.

4.3.2 Cycle life of battery

The cycle life of a battery refers to how many full charge and discharge a battery do before degrading its performance gradually. It’s another extremely important factor because if a battery has a value of 200 cycle life then after about a year of operation it’s battery will need to be replaced which is not practical at all. Nobody will buy such an EV. **Table 4.1** shows a comparison of some of these parameters between the three batteries. The green highlighted values refer to the best parameters among all the three batteries.

Table 4.1 Comparative analysis of the three batteries

	Lead acid	**Ni-mh**	**Li-ion**
Specific Energy (Wh/kg)	30-60	60-120	**100-275**
Energy Density (Wh/L)	60-100	100-300	**200-735**
Specific Power (W/kg)	75-100	250-1000	**350-3000**
Cell Voltage (V)	2.1	1.35	**3.6**
Cycle Durability	200-300	200-500	**500-3000**
Typical Battery Cost	**$25-$30**	$60	$90-$100

CHAPTER 5

CONCLUSION

5.1 Concluding Remarks

In this thesis, our objective was to analyze the performance of different batteries used in electric vehicles. To fulfill this objective at first we have done extensive literature review of the batteries used in electric vehicles since late 1990. Although, EVs and HEVs were in the market since the early 1999 or earlier but all electric vehicles started to come to the market after 2010 with a decent range. Low battery cycle life, low specific power, high cost of batteries were the key variables that hinders the revolution of the EV. Between this period, most of the EVs were hybrid EV with low efficient battery, small range and a small battery pack.

As we have shown in literature review, the GM EV1 was the first all-electric vehicle introduced to the mass consumer by one of the biggest automakers in the world between 1996 to 1999. It utilizes both lead acid and NiMH battery with a battery size of 16.5 to 26 kWh. The range of this electric vehicle was 126 to 228 km. Ultimately, this EV fails to attract mass consumers because of the following reasons -

- 126 to 228 km range is not enough for a typical consumer.
- recharge time of this EV was not fast enough
- lack of charging station
- low cycle life of lead acid and NiMH batteries

Overall, these shortcomings made almost all the EVs of early 2000 non practical option for mass consumers. If we have a close look at the problems, we notice that almost all of the problems are closely related to battery. Hence the quest for better battery has started for EV where most of these shortcomings will be terminated or reduced up to a certain level.

We have tried to introduce this evolving of EV batteries. Our simulation model of an EV in MATLAB Simulink utilizes three batteries those are mostly used in EVs so far - lead acid, nickel metal hydride and lithium ion. We have set the exact same parameters during the simulation of all three batteries. We have a used a battery of 2.5kWh with a nominal voltage of 50 V. From the simulation result, we have considered three battery parameters for comparison. We have observed SOC of battery, nominal voltage of battery as well as battery current. We have found that in terms of SOC consumption nickel metal hydride is a great option. The battery current remains the same for all three batteries because of the same input parameters for all three batteries. However, battery voltage curve shows that lead acid fluctuates most during acceleration and deceleration of the EV where Li-ion and NiMH acts well during acceleration and deceleration.

Specific energy which determines the weight of the battery pack, cycle life which determines the longevity of battery, recharging speed and other parameters are vastly important to choose the perfect battery for EV. Analysis of these parameters along with the simulation shows us which battery to choose and which performs the best for an EV. This study concludes that lithium ion is the best performing battery for EV in terms of a best overall package.

5.2 Future Scopes

The objectives of this work was to analyze the performance of EV batteries to give readers an idea why Li-ion battery is being extensively used in recent years as well as giving an overall overview of EV batteries. In light of this objectives other energy storage solutions can be explored such as fuel cell and FCVs. FCVs are getting more and more researchers attention because hydrogen has far far higher energy density compared to typical batteries. Also, hydrogen is much more energy efficient and environment friendly.

Moreover, the primary hindrance of FCVs are hydrogen production cost. If the production cost of hydrogen can be reduced FCV will be much more attractive than current EV.

Batteries are now also considered for large scale energy storage devices. The requirements for stand still large scale energy storage devices are completely different than that of an EV. Keeping that in mind performance of energy storage devices can be explored as a whole.

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