1
Introduction

1.1 INTRODUCTION

With advancement in technology and continual change in human lifestyle, the energy consumption rate has accelerated around the world-wide. The energy consumption is one of the key factors which indicate the human development. The energy consumption depends mostly upon the energy reservoirs and expertise on its extraction technology of that country. The energy resources are classified into two categories- renewable and non-renewable energy resources. The renewable energy resources are non-depleted in nature e.g. solar energy, wind energy, tidal energy, geothermal energy, etc. These renewable energy resources are long lasting compared to non-renewable energy resources. The non-renewable energy resources (coal, hydrocarbon based liquid fuel (petrol, diesel), natural gas, nuclear fuel, etc.) are limited up to reservoir capacity. The depletion rate of these resources depends upon consumption rate.

The worldwide energy consumption in past and in future (with projection) is presented in Figure1.1 [EIA, 2016]. The global energy consumption was 549×10^{15} Btu in year the 2012 which increases up to 815×10^{15} Btu in forthcoming year 2040 with an average annual 1.4% growth rate. This energy is obtained from the different energy resources as shown in Figure 1.1. From past one decade due to appealing global warming concern and its impact on climate change, there is a shift in the use of energy resources. The reliance on green energy resources, such as solar and wind, has been increased since past decade which can also be clearly visualized from Figure 1.1.

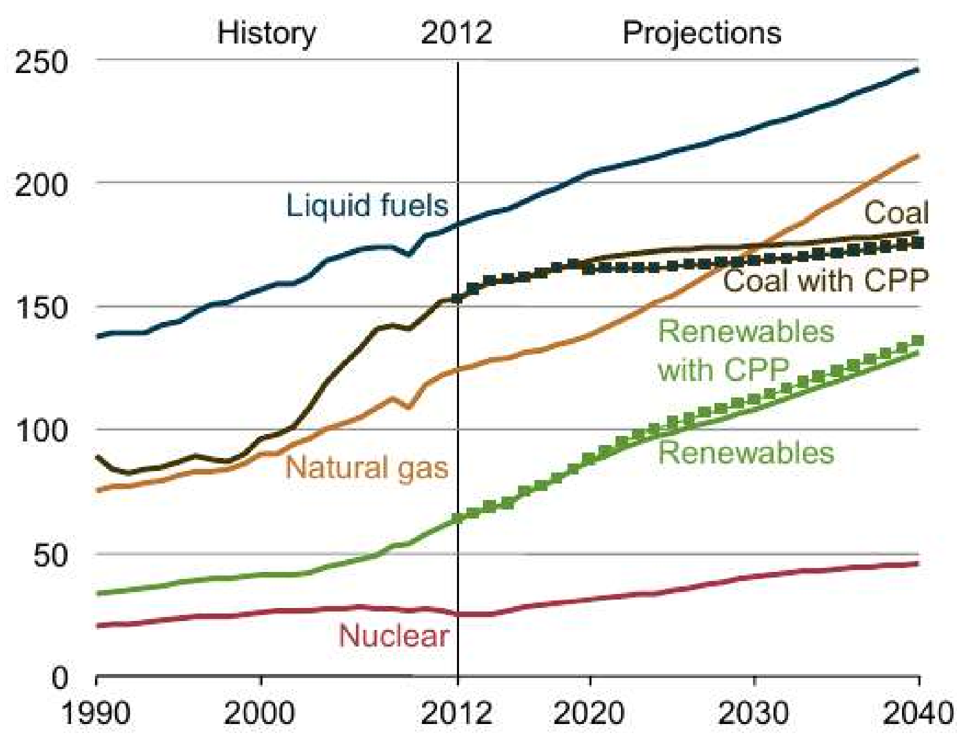

Figure 1.1: Total world energy consumption (quadrillion Btu) by energy resources, 1999-2040 (*Source*: EIA, 2016)

The energy consumption occurs in four sectors namely: transport, industrial, electric power generation, residential and commercial applications. The annual energy consumption in each sector by different energy resources is forecasted and shown in Figure 1.2 [AEO, 2009]. The contribution of renewable energy resource in terms of percentage is 10% in transport, 18% in industrial, 6% in residential and commercial and 15% in electric power. It showed that the renewable energy sector plays contributory roll in each sector.

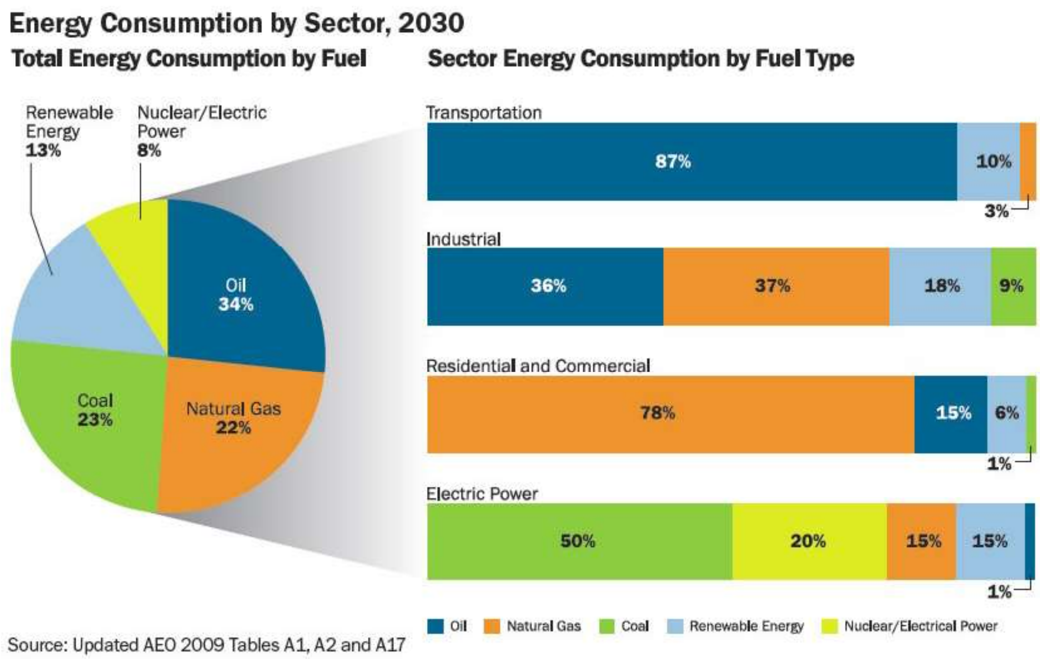

Figure 1.2: Total world energy consumption by sector 2030 (*Source*: AEO, 2009)

Bloomberg New Energy Finance's predicted that the new power generation of 3500 GW capacity will be build up to 2030 which includes 70% renewable technology taking into account hydro power. This projection reported that the major share will be covered by wind and solar energy [ThinkProgress, 2013].

The energy generated by solar and wind technology is mostly dependent on weather conditions at particular geographical location. The challenges are not only in generation of energy but also in distribution to meet the demand of energy as when required. The distribution of energy mainly depends on requirement of different energy consumption sectors at particular period of time. The industrial sector consumes more energy (31%) compared to other (domestic 22% and transport 28%) sectors [AER, 2011]. There is utmost need to fulfill the demand of energy supply for sustainable development of society. This may be achieved by adopting an efficient energy storage technology. There are various energy storage technologies which are classified in two broad categories namely: electrical energy storage (EES) and thermal energy storage (TES). The EES system includes mechanical energy storage (fly wheel, pumped hydro, gravity, compressed air, etc), chemical energy storage (CES) such as hydrogen, bio-fuel, bio-diesel, electrochemical energy storage (ECES) as super-capacitors and batteries, superconducting magnetic energy storage, cryogenic energy storage [Aneke and Wang; 2016]. The selection and application of EES depend upon the need for commercial and societal benefit.

1.2 CLASSIFICATION OF BATTERIES

The typical battery has four essential components as anode, cathode, separator and electrolyte. The major difference in various batteries is due to the electrode (anode and cathode) material and electrolyte components. These components decide the characteristics of battery as- open circuit potential (OCP), specific charge-discharge capacity, rate performance, cyclability, depth of discharge, columbic efficiency, cost factor, etc.[Linden and Reddy, 2002].

Further, batteries are classified into two categories: primary and secondary. The primary batteries are also called non-rechargeable batteries. It is used normally for low power applications. The secondary batteries are also known as rechargeable batteries and mostly used for high power applications. Among primary batteries, the most commercially viable are the zinc-carbon and the alkaline-manganese batteries. The secondary batteries are varied from most versatile lead acid battery to latest lithium ion based batteries.

The lithium ion batteries involve the movement of Li-ion between cathode and anode through electrolyte. There are different types of lithium ion batteries namely- lithium cobalt batteries, lithium-manganese batteries, lithium iron phosphate batteries, lithium sulfur batteries, lithium titanate batteries, lithium ion polymer batteries and thin film lithium ion batteries [Linden and Reddy, 2002]. The various characteristics (anode material, cathode material, nominal voltage, energy density, theoretical specific cathode capacity, achieved specific cathode capacity) of commercialized Li ion batteries are tabulated in table 1.1.

Table 1.1: Common Parameters of Three Different Frameworks based Li-ion Batteries (*Source:* Julien et al., 2014)

Anode	*Cathode*	*Nominal Voltage*	*Energy density*	*Theoretical Specific cathode capacity*	*Achieved Specific cathode capacity*
		V	Wh/kg	$mAhg^{-1}$	$mAhg^{-1}$
Graphite	$LiCoO_2$	4.2	195	274	140
	$LiFePO_4$	3.45	90-130	170	160
	$LiMn_2O_4$	4.1	420	148	120
	$LiMn_{1.5}Ni_{0.5}O_4$	4.7	650	146.72	120

1.3 WORKING PRINCIPLE OF LITHIUM BATTERY

The schematic diagram of lithium ion battery is presented in Figure 1.3. The lithium ion battery consists of negative electrode (Li-metal), positive electrode (for example: $LiMn_2O_4$ for 4 V or $LiMn_{1.5}Ni_{0.5}O_4$ for 5 V), electrolyte (1M $LiPF_6$, (1:1) EC+DMC) and separator (Whatman filter GA/F or Celgard 2400). During charge process, the Li^+ ions are librated from positive electrode and inserted into negative electrode. The reverse mechanism takes place during discharge process i.e. Li^+ ions are librated from negative electrode and inserted into the positive electrode (Li-metal foil). The reaction mechanism is illustrated through equation 1.1 to 1.4 [Chenet et al, 2016]. The electrolyte is the media through which the Li-ion transports from negative electrode to positive electrode and vice-versa. The separator plays a role as lithium ion filter and protect from shorting the two electrodes. The porosity of electrodes and separator material play an important role for Li-ion diffusion during charge-discharge process.

During charge process reaction mechanism at

Negative electrode $xLi^+ + x\,e^{-1} \longrightarrow x\,Li$ ………..(1.1)

Positive electrode $Li_{1+x}Mn_2O_4 \longrightarrow LiMn_2O_4 + x\,Li^+ + x\,e^{-1}$ ………..(1.2)

During discharge process reaction mechanism at

Negative electrode $x\,Li \longrightarrow x\,Li^+ + x\,e^{-1}$ ………..(1.3)

Positive electrode $LiMn_2O_4 + x\,Li^+ + x\,e^{-1} \longrightarrow Li_{1+x}Mn_2O_4$ ……..…..(1.4)

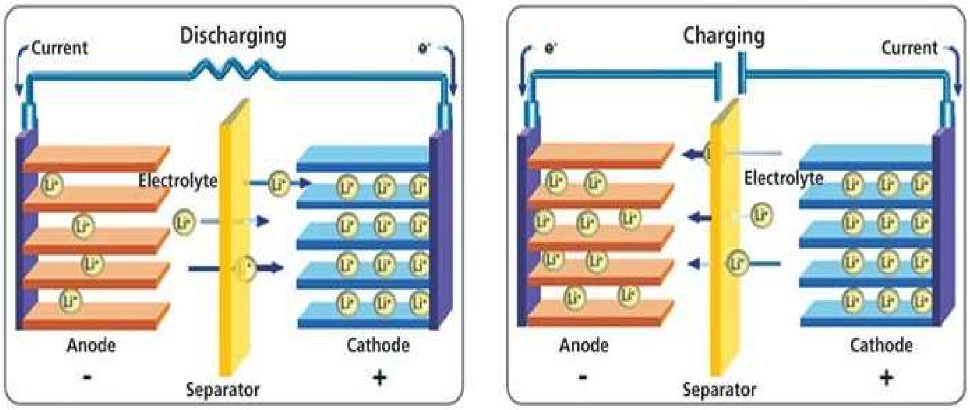

Figure 1.3: Working Mechanism of a Li-ion battery during discharging and charging (*Source*: Rdmag, 2014)

1.4 CHARACTERISTIC PARAMETERS OF BATTERY

To operate any device such as cell phone, clock, TV, electrical vehicle; by the batteries, it is essential to satisfy at least two operating parameters e.g. operating voltage (V) and minimum current delivered. However, to operate a device without any interruption, the current supply and potential must be continuously sustained as per technical specification. The selection of suitable battery is depending not only on environmental condition but also on battery parameters and its application. Here, the important battery parameters are defined in brief:-

1.4.1 Nominal Voltage (V): It is the average of potential difference in fully charged condition and end-of-discharge condition. This potential is used to rate the potential difference of battery.

1.4.2 Capacity (mAh): It is related to amount of charge that a battery delivers at rated voltage. It is measured in unit of milliampere hours (mAh) for low capacity batteries and in unit of ampere hour (Ah) for high capacity batteries. The capacity of battery depends upon the amount of active electrode materials.

1.4.3 Energy Density (Wh/kg): The energy density is a measure of total energy stored into the battery. It can be defined in two ways - energy per unit volume and energy per unit mass. The amount of extractable energy is measured in specific energy density i.e. energy per unit mass.

1.4.4 Power Density (W/kg): It is a parameter which measures the maximum current can be withdrawn at rated voltage. Power density and energy density are used to compare battery technology for desired application.

1.4.5 Columbic Efficiency: It is a ratio of discharge capacity to charge capacity of a battery. It indicates about effective utilization of stored charge during discharge process.

1.4.6 Rate Performance: The rate performance is generally defined in terms of C-rate. It shows that at which rate, the current can be withdrawn to run the device. The current can be supplied to store the charge without affecting the capacity of battery. The 1C rate refers to amount of current withdrawn from the battery such that it becomes fully discharge state in one hour.

1.4.7 State of Charge and Depth of Discharge: The state of charge (SOC) indicates the capacity is available for discharge whereas the depth-of-discharge indicates the amount of capacity has been reduced. Both parameters are related to each other by following relation i.e.

$$\textit{State of charge (SOC) \%} = 100 - \textit{Depth of discharge (\%)}$$

1.4.8 Cyclability: It estimates the lifetime of a battery i.e. number of charge-discharge cycles before becomes unusable.

1.4.9 Internal Impedance: It is a indicator of total impedance offered by the battery due to its internal components i.e. current collector, bulk electrodes material, diffusion resistance, solid electrolyte interface resistance, etc. It limits the peak amount of current delivered by the battery.
1.4.10 Temperature Dependence: The temperature affects the performance of battery reversely. At low temperature, the electrolyte may be freeze which reduces the Li-ion diffusion and due to that specific capacity and cyclability of battery affect. At high temperature, the decomposition of electrolyte and degradation of electrode material are responsible for reduction in battery capacity.
1.4.11 Cost Factor: The cost of raw material affects the commercialization and utilization of particular battery. High cost of battery may be not affordable for daily use but may be applicable for specific purpose such as space and defense application. The raw material and processes must be cheap otherwise the battery cost will be raised.

1.6 WHY IS THE LI-ION BATTERY?

The availability of comparative assessment on various electrical energy storage technologies suggests that the Li-ion based storage technology has potential to meet the future energy supply-demand gap, to make reliable transport sector and long life of smart gadgets. The specific energy (Wh/kg) and specific power (W/kg) are assessed by the Ragone plot. The Ragone plot is used to compare the performance of energy storage devices. The Figure 1.4 shows that Ragone plot of Lead acid, supercapacitor, nickel-cadmium (Ni-Cd), nickel metal hydroid (NiMH), Li polymer and Li ion battery technologies [Bossche et al, 2006].

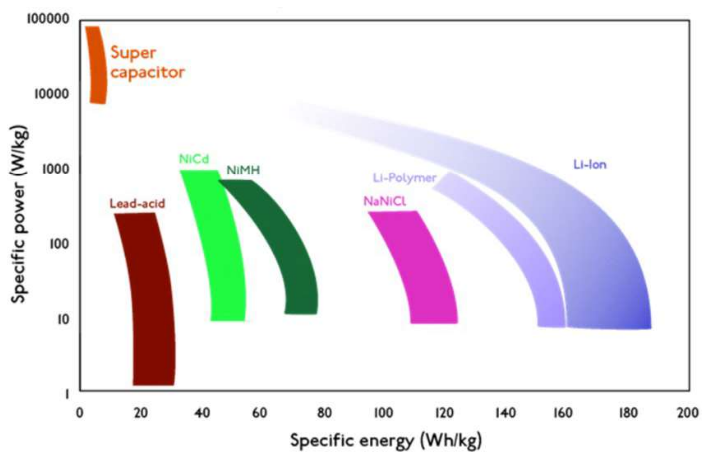

Figure 1.4: A Ragone plot of different electrical energy storage technologies (*Source*: Bossche et al.; 2006)

1.7 ELECTRODE MATERIALS FOR LI-ION BATTERY

The lithium-ion battery technology is based on anode material, normally graphite or carbon based, and different cathodes materials. The capacity of battery mostly depends upon positive electrode material (cathode). The various lithium ion battery technologies are commercialized and available in market based on positive electrode namely:- lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium manganese nickel oxide (LMNO). Based on these cathode materials, battery differs in operating potential, capacity (mAh), energy density (volumetric and gravimetric) and performances. The potentials and capacities of various cathodes are shown in Figure 1.5 [Goodenough and Kim, 2009].

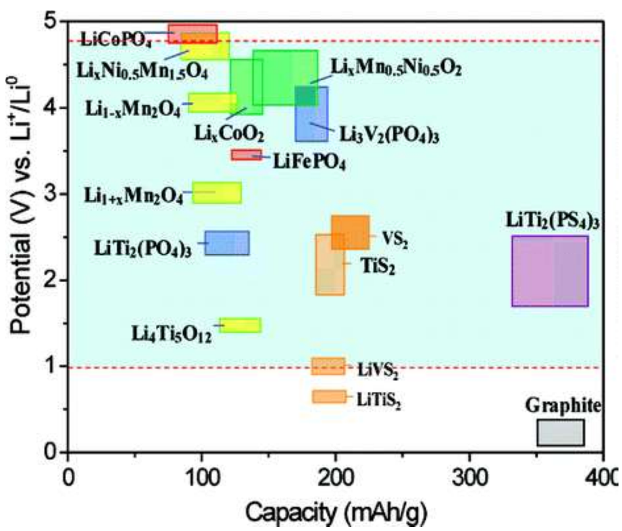

Figure 1.5: Potential and capacity of various cathodes for Li-ion battery (*Source*: Goodenough and Kim, 2009)

1.8 CLOSING REMARKS

It is conclusive from the above-discussed scenario that Li-ion battery technology is offering best option to meet future challenges. The matured eco-friendly and cost-effective technology has to develop in a sustainable way by taking into consideration of future need in different application sectors.