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Battery technologies and its future prospects

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In today's world, machines and a plethora of electronic devices surround humans. The growing market of electronic and electrical devices and thrust to sustainable developments is a driving force for the development of batteries as energy storage media, which are extensively used to power small gadgets to big cities. Many types of battery technologies are currently in use and each has their own advantages and disadvantages. The present review work aimed to discuss and compare the various battery technologies and its associated financial/technological challenges. Additionally, various battery technologies are also discussed covering various aspects of the materials for future batteries to provide a research direction in the rapidly emerging field of energy storage systems.

Keywords: Battery technologies, lithium-ion battery, safety issues, energy storage.

Introduction

In today's world, machines surround humans and there is a plethora of electronic devices to make life easier and comfortable. Recent advancement in technology is visible in the form of smart phones, tablets, smart homes, smart automobiles etc. These advancements are an indication that world is now entering into a new era of digitalization and automation considering the requirements of sustainable development. An important aspect of sustainable development is the use of emission-free energy. Under the Paris Agreement[1], major countries have pledged to limit the global average temperature rise below 2°C. In this regard, International Energy Agency (IEA) has estimated that at least 20% of road vehicles should run on alternative energy by 2030[1]. Renewable power capacity is set to expand by 50% between 2019 and 2024, led by Solar Photo Voltaic (PV) system[3]. Renewable energy sources rely on the energy storage system and research activities in the field of a battery is increasing with the shift in the current energy scenario. A battery is a device with one or more electrochemical cells which coverts chemical energy to electrical energy. Various combinations of one or more electrochemical cells are shown in Fig. 1.

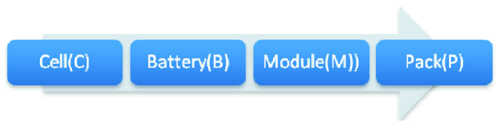

Fig. 1. Arrangements of cells as storage device.

Batteries are very common and are present everywhere around us but there are certain concerns like safety, commercial viability, cost-effectiveness, sustainable battery materials, charging/discharging rate that has affected the growth and popularity of batteries as energy sources[4]. These concerns have affected the advancement in battery technologies in comparison to the development in electronic devices. The present work reviews the battery technologies with reference to the parameters like energy density, energy efficiency, materials, cost, safety and other desired parameters for sustainability and reusability. Further, the paper discusses the challenges in the existing technologies and the future prospects in terms of new materials choices along with alternative battery technologies having scope of replacing Lithium ion battery (LIB) technologies.

History of battery technologies

The earliest battery technology dates back 2000 years when Parthians used to generate 1 to 2 volt of electricity by a galvanic cell made up of clay and iron rod surrounded by copper tube filled with vinegar solution[5]. In 1800 AD, according to Alessandro Volta, who discovered an early battery of modern times, certain fluids generate continuous flow of electric power when used as conductor. Other important shifts in the development of batteries are listed in Table 1. Initially, the batteries were developed by using widely available and popular anode and cathode materials.

Table 1. Major shift in battery technologies

Year	Technology
1836 AD	A primary cell (Daniel Cell) was developed.
1860 AD	A secondary cell (Lead acid battery) was developed[6].
1866 AD	An improved primary cell (Leclanche cell) was developed.
1886 AD	First dry cell (a variant of Leclanche cell) using Zinc Carbon Cell.
1991 AD	John B. Goodenough developed Lithium ion battery (LIB).

However, with the technological advancement in chemistry and material science, the battery technology evolved progressively with the new choice of materials.

Existing battery technologies

Development of energy from renewable sources and battery as energy storage for the power supply in the city power systems is a new sustainable solution for energy crisis, energy output fluctuations, and power unpredictability[7]. Battery as electrical energy storage (EES) system is widely used in electrical grid for load leveling applications to store the energy and supplies it during energy shortage/increased energy demand as shown in Fig. 2a[8]. Available battery technologies can broadly be categorized into three groups as shown in Table 2. Among the several battery technologies available since many years, Fig. 2b shows the usage of LIB, which is 88%[9,10] until 2016. Fig. 2b also illustrates the changing trend of groups (a) and (b) of battery technologies and highlights how LIB is replacing most of the battery technologies along with its increasing applicability, which must be due to its lightweight, and highest oxidation potential. While LIB technologies have been matured, there are significant possibilities in the growth of group (c) battery technologies. This is due to the advancement in the field of nanomaterial synthesis such as synthesis of graphenes and MXenes. According to the recent analysis by Mckinesy[11] in 2018, lithium, cobalt, and nickel for batteries had estimated global value of ~$5 billion, where the share of cobalt was ~60%, lithium was ~30% and highly pure nickel for batteries was ~10%. Further, the performance degradation of lithium ion batteries is due to loss of power or reduced discharge power at low temperature or because of overuse and aging.

This presents the need of searching for other optional material candidates[13]. Also, in view of future metal security and limited availability of lithium metal, other metallic com-

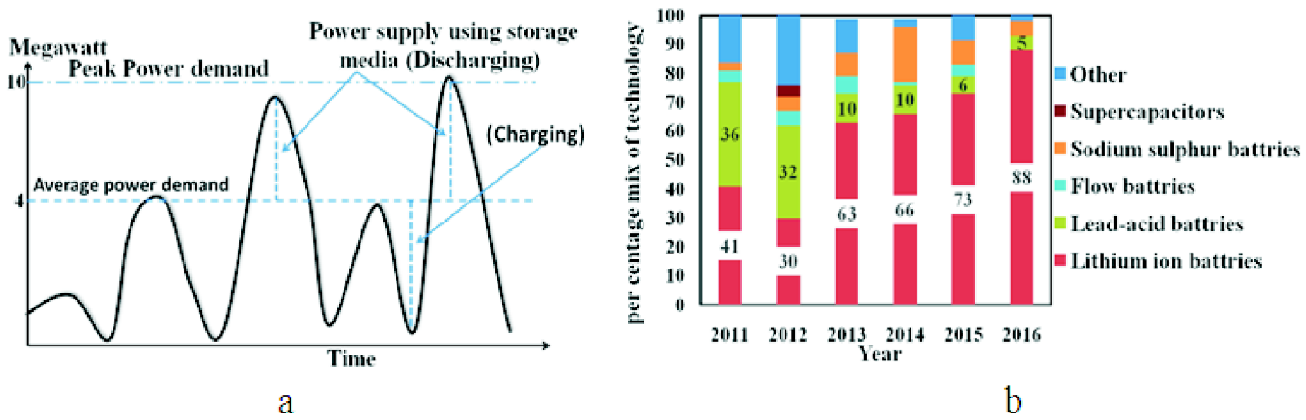

Fig. 2. (a) Schematic plot of load levelling applications of EES system, (b) percentage mix of battery technology[10].

Table 2. Broad classification of battery technologies

Classifications	Types	Battery examples	
Group (a)	Primary cells	Carbon/zinc	Li/$SOCl_2$
	Secondary cells	NiCd	LIB
	Flow battery	ZnBr	ZnCl
Group (b)	Dry cell	NiMH	NiCd
	Alkaline battery	Zn/MnO_2	$BaSO_4$-Zn/MnO_2
	Pure metals	Carbon/zinc	NiMH
Group (c)	Compounds/composites	LIB	$Li_{15}Si_4$
	Nanomateials	$Ti_3C_2T_X$ (MXene)	Ti_3CNT_X (MXene)

positions such as Nickel Metal Hydride battery (NiMH), Lithium-ion polymers, Reusable alkaline batteries are changing the battery market dynamics rapidly. Growing demand of rechargeable batteries is the cause of growing research for alternative materials. In Table 3, for rechargeable battery technologies, financial and technological comparison establishes the reason for the market dynamics. This may be due to the cost incurred and the material availability constraints. Since lithium is comparatively rare, although lithium based batteries are advantageous, there is a significant thrust to shift to some new materials.

Financial and technological challenges in battery technologies

The global battery market is expected to grow from USD 14.08 billion in 2016 to USD 17.25 billion by 2021 at a Compound annual growth rate (CAGR) of 4.15%[14]. The market of battery is expected to grow rapidly to become the largest market in Asia Pacific (APAC). Therefore, it becomes important to identify the financial and technological challenges battery technologies are facing for its growth. The major financial challenges are shown in Fig. 3. The research and developments in battery technologies nowadays significantly focuses sustainability and commercial viability. In this regard, although, the performance of nickel-based batteries in terms of gravimetric and volumetric energy density is less as compared to LIB (Fig. 4), there is a need to bring improvements in the specific energy of Nickel based (NiMH) or other battery technologies as lithium supply will run out on long-term basis and it is toxic[15]. Redox flow batteries and Advanced Redox flow batteries for large-scale storage (10 kW–10 MW) applications are common candidates having most of the desired benefits[16]. Further, Aqueous Lithium Flow Battery is also a good option for stationary application and recently sulphur and manganese flow batteries are also researched by leading research universities to decrease the burden on

Table 3. Financial and technological comparison of battery technologies[12]

Comparative parameter	NiCd	NiMH	Lead acid	Li-ion	Li-ion polymer	Reusable alkaline
		Technological parameters				
Gravimetric energy density (Wh/kg)	45–80	60–120	30–50	110–160	100–130	80 (initial)
Internal resistance in mΩ	100 to 2001	200 to 3001	<1001	150 to 2501	200 to 3001	200 to 20001
Fast charge time	1 h	2–4 h	8–16 h	2–4 h	2–4 h	2–3 h
Overcharge tolerance	Typical Moderate	Low	High	Very low	Low	Moderate
Self-discharge/Month (room temperature)	20% 4	30% 4	5%	10% 5	~10% 5	0.30%
Cell voltage (nominal)	1.25 V	1.25 V	2 V	3.6 V	3.6 V	1.5 V
Maintenance requirement	30 to 60 days	60 to 90 days	3 to 6 months	Not req.	Not req.	Not req.
		Financial parameters				
Typical battery cost (US$)	$50 (7.2 V)	$60 (7.2 V)	$25 (6 V)	$100 (7.2 V)	$100 (7.2 V)	$5 (9 V)
Cost per cycle (US$)	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10–0.50
Commercial use since	1950	1990	1970 (sealed)	1991	1999	1992

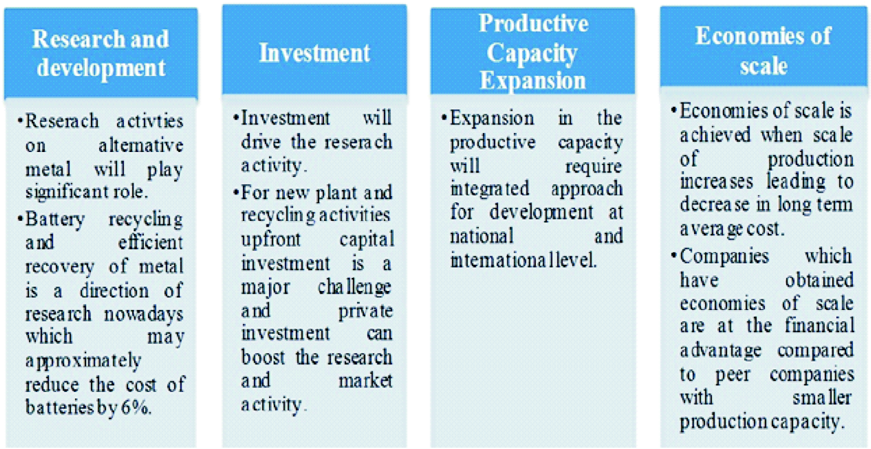

Fig. 3. Major financial challenges in the growth of new battery technologies.

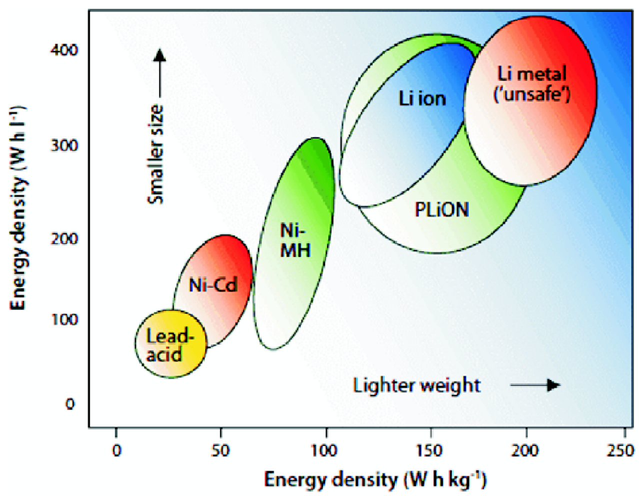

Fig. 4. Comparison of the different battery technologies in terms of volumetric and gravimetric energy density[17].

lithium. Finding out the optimum solution to self-discharge problem and less specific energy density of NiCd and NiMH battery is one of the major chanllenge in the commercial comeback of these technologies [1818-19]. However, usage of $LaNi_5$-type electrodes brings out higher hydrogen mass capacity, increased safety of NiMH batteries and reduced cost. This has become a important reason for growing demand of NiMH batteries for hybrid electrical vehicles (HEV). Other technological challenges in the growth of the batteries are issues related to (a) Recycling, toxicity, overheating, explosion, (b) Limited skilled battery system operating personals, (c) Insufficient accreditation and trained designers and installers, (d) Disposal and recycling guidelines and (e) Emergency response systems. Out of these problems, safety concerns and design standards requirement has become bigger hurdle for the approval by designated agencies and acceptability for the new technologies. For safety assessment industry standards, such as those set by the International Society of Automotive Engineers (SAE), International Organization for Standardization (ISO) etc., should be followed by battery manufacturers. In order to ensure mechanical safety, tests such as mechanical shock, drop test, penetration test, crush test, rollover and vibration test should be conducted at cell, battery, module and pack level. Another major concern is environmental issue i.e. carbon footprint of battery manufacturing and recycling units. There are environmental benefits of Vanadium redox flow batteries, which lie in the high recyclability of vanadium that outweigh the negative impact of their production cost and low energy density. Their simple and flexible design makes it easier to recycle up to 10–20 times. Research is going on to raise redox flow batteries to its full potential through cost and size reduction with high energy density[20].

Future prospects in the development of battery technologies

The future of the battery technologies is largely dependent on the following points for wide market acceptability and growth keeping safety standards as prime criteria:

(i) Accelerated battery material discovery and interface engineering: The material related issues such as self discharge, exfoliation, loss of porosity, cracks, structural changes etc. should be considered while developing new materials. *(ii) Smart sensing and self-healing functionalities:* Self healing polymer coats can be used to repair cracks developed due to electrochemical reactions. *(iii) Cell design and manufacturability*: Design of cell should be done using best practices to ensure the ease of manufacturing with efficient functionality and safety. *(iv) Flame retarding property*: Mixing of flame suppressing agents (fluorinated compounds) will pave the way for batteries with enhanced safety of batteries[21]. *(v) Recyclability:* Lead acid battery is matured enough and technology of recycling to lead acid battery is simple. As of now, 50% of lead supply comes from recycled lead acid batteries. The toxicity of lithium pose difficulty for its recycling compared to semi-toxic nickel. Therefore, the studies related to recyclability of battery materials for nickel based and other advanced polymer or composite based batteries should be promoted.

Conclusions

The present work discussed the various existing battery technologies and their constraints. There is a limited availability of lithium so the other optional materials for energy storage applications are required to be researched focusing recycling and safety issues. Growing demand for secondary cells for grid and automotive applications is redirecting the researchers' attention towards developing nickel based, lithium polymer and reusable alkaline-based batteries once again. Development of batteries that are suitable for automotive applications, which require rapid charging, high specific energy ensuring its safety for static as well as dynamic applications is another dimension to work on. It is also inferred from the present work that there will be a huge demand of number of testing facilities to perform safety test from cell level to battery pack level, which will significantly govern the battery market dynamics in future.

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