Emergent energy storage sector in the developing world: A technological and strategic perspective

Apoorv Shaligram[1*], Uttam Kumar Sen[2]

[1] Alchemist E-Vaahan Pvt. Ltd., India; [2] Log 9 Materials Scientific Pvt. Ltd., India; [*] email of the corresponding author: apoorv@e-vaahan.com

Abstract

With the focus on clean energy, efficient devices and electric mobility solutions, the market for energy storage is on the rise in the developing world. In this paper, the requirements of Indian energy storage market have been highlighted based on the different categories of applications. An in-depth study of the utilitarian advantages and disadvantages of different energy storage technologies has been conducted. Based on this, suitable energy storage technologies for different applications have been suggested. We have further delved into the elements required for all the feasible energy storage technologies. The availability of strategic reserves of these minerals in India have been examined. We have calculated the elemental requirements for different technologies, normalized to their energy storage capacity. Finally, we have suggested technologies to achieve a best-case scenario for the Indian energy storage sector from technological as well as a strategic viewpoint, minimizing the import dependency of raw materials.

Keywords: energy storage; battery; lithium-ion; India, ASEAN.

Introduction

Climate change and environmental pollution have been the focus of global discourse over the past few years. In the Indian context, rising fuel prices and energy security must be added to the discussion. This has led to a policy shift favoring clean and energy efficient technologies such as energy-efficient household appliances (e.g., Fans, LED lights), electric vehicles and utilization of renewable energy. With this shift, the market for energy storage is projected to grow significantly.[1,2,3] If the energy storage industry is to develop and support India's energy and mobility needs, it should be based on three key aspects: 1. Technology development; 2. Availability of raw materials; 2. Sustainability towards environment. The new technologies should be sustainable from point-of-view of environment, technology, economics, and geopolitics. In this paper, an attempt has been made to compare different energy storage technologies across different figures of merits and applications to evaluate their sustainability from an Indian perspective.

Battery technology development in India

In the last couple of years several players, be it manufacturing giants like Suzuki, Exide or small SME players have set up their Lithium-ion battery packs manufacturing in India for different applications. [4] However, in all these cases Lithium-ion cells are imported. Recent push by the Government of India to manufacture Lithium-ion cells in India has triggered several companies to work on plans for Lithium-ion cell manufacturing (Table I). Although most of the announcements are in the initial stage, they are expected to kick start over the next couple of years. Based on the reports available in the public domain, it can be said that the above companies will start the production of Li-ion cells by acquiring the technical know-how from foreign established players. Apart from

TABLE I

COMPANIES SETTING UP LI-ION CELL MANUFACTURING IN INDIA

Company Name	Announcements
Tata Chemicals	Planning to set up a 1.7 GWh of Li-ion cell manufacturing in Dholera City in Gujrat (7).
Li Energy	Planning to set up 150 MW of Li-ion cell fabrication facility in Thondi, Tamil Nadu by End of 2021 (7).
BHEL	Planning to set up 1 GWh of plant in collaboration with LIBCOIN, a cross country consortium. They have also licensed ISRO's Li-ion cell technology to produce Li-ion cells for space application (1).
Raasi Power	Proposed to setup Li-ion cell fabrication facility in Tamil Nadu (1).
Munoth Industries	Proposed to setup Li-ion cell fabrication in Tirupati, Andhra Pradesh (1).

TABLE II

START-UPS WORKING ON ADVANCED CELL TECHNOLOGIES IN INDIA

Company name	Technology
GODI energy	A Hyderabad based start-up, working on next generation battery technology such as solid-state batteries[1]
Virya Batteries	A Mumbai based start-up, incubated at IIT Bombay indigenously developing safe batteries that do not catch fire.[1]
Gegadyne Energy	A Mumbai based start-up, developing supercapacitor-based battery that can be charged at a faster rate as compared to conventional batteries.[1]

these, there are few start-ups working towards developing their own advanced battery technology (Table II). Apart from technology development for lithium-ion cells, there are some serious efforts to produce materials for Li-ion cells at commercial scale. Himadri Speciality Chemicals, a Kolkata based conglomerate has developed anode material for Li-ion cells.[5] Another speciality carbon manufacturer, Epsilon Carbon Pvt. Ltd., is setting up their anode material production facility at Bellary, Karnataka.[6]

Technologies

To keep the scope of this paper concise and limited, only electrochemical energy storage technologies have been considered. Fuel cells have not been considered as the operating principle of fuel cells and the infrastructure required to accommodate fuel cells in applications differ significantly from those for batteries and electrochemical supercapacitors. The technologies covered here are as follows: 1. Lead Acid batteries; 2. Nickel Metal-hydride (Ni-MH) batteries; Li-ion battery family — $LiCoO_2$ (LCO) cathode; $LiMn_2O_4$ (LMO) cathode; $LiFePO_4$ (LFP) cathode; Low Nickel content $Li(Ni_xMn_yCo_z)O2$ (NMC; x<0.7) cathodes; High Nickel content $Li(Ni_xMn_yCo_z)O2$ (NMC; x>0.7) or $Li(Ni_xCo_yAl_z)O_2$ (NCA; x>0.80) cathodes; $LiMn_{1.5}Ni_{0.5}O_4$ (LMNO) cathode; Li_2MnO_3 composite cathodes; $Li_4Ti_5O_{12}$ (LTO) anode; Si, Si-C & Si-C-graphite composite anodes; Solid State batteries. 3. Sodium-ion (Na-ion) batteries; 4. Supercapacitors. Table III describes the different technologies, their advantages, and disadvantages. Conventionally, battery technologies have been compared across figures of merit such as energy density (both gravimetric and volumetric), power density, life, safety, and price. However, since the objective of this work is to establish the most suitable battery technology options for Indian markets, two more metrics are of importance, namely import dependence and environmental impact. Analysis based on these two metrics is necessary if the battery industry is to sustainably cater to Indian needs in the foreseeable future.

TABLE III

COMPARISON OF DIFFERENT ELECTROCHEMICAL ENERGY STORAGE TECHNOLOGIES

Technology	Description of system	Advantages	Disadvantages
Lead Acid batteries [1,1]	$Pb + PbO_2 + 2H_2SO_4$ $2PbSO_4 + 2H_2O$	Low cost, recyclability	Low energy density, low power density, low life
Nickel-Metal Hydride batteries [1,1,1]	$M + Ni(OH)_2 \rightarrow MH + NiO(OH)$ M is intermetallic compound consisting of rare earth metals	No memory effect (improvement over earlier NiCd batteries), recyclability, low temperature performance, safety	Low energy density, requires rare earth metals, sensitive to overcharge, high self-discharge and low coulombic efficiency, high cost
Li-ion ($LiCoO_2$ – Graphite) [1,1,1]	$LiCoO_2 + xC_6 \rightarrow Li_{(1-x)}CoO_2 + xLiC_6$ ($x \leq 0.5$) Oxidation state of Co changes from +3 to +4 during charging	Energy density, cycle life, High coulombic efficiency	Overcharging protection required (to avoid explosion), high cost, requires cobalt
Li-ion ($LiMn_2O_4$ – Graphite) [1,1,1]	$LiMn_2O_4 + xC_6 \rightarrow Li_{(1-x)}Mn_2O_4 + xLiC_6$ ($x \leq 0.8$) Oxidation state of Mn changes from +2 to +4 during charging	Low cost, high safety, high power density	Low energy density, low life, overcharging protection required (to avoid degradation), degradation at high temperature
Li-ion ($LiFePO_4$ – Graphite) [1,1]	$LiFePO_4 + xC_6 \rightarrow Li_{(1-x)}FePO_4 + xLiC_6$ ($x \leq 1$) Oxidation state of Fe changes from +2 to +3 during charging	High safety, high power density, cycle life, low toxicity	Low energy density
Li-ion (Low Nickel $Li(Ni_xMn_yCo_z)O_2$ – graphite) (xyz = 111, 532, 622) [1,1]	$Li(NiMnCo)O_2 + xC_6 \rightarrow Li_{(1-x)}(NiMnCo)O_2 + xLiC_6$ ($x \leq 0.5$-0.65) Oxidation state of Ni, Co changes from +3 to +4 during charging	Energy density, reduced cobalt and cost compared to LCO	Overcharging protection required (to avoid explosion), requires nickel and cobalt
Li-ion (High Nickel $Li(Ni_{0.8}Mn_{0.1}Co_{0.1})O_2$ / $Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$ – graphite) [1,1,1,1,1]	$Li(NiMnCo)O_2 + xC_6 \rightarrow Li_{(1-x)}(NiMnCo)O_2 + xLiC_6$ ($x \leq 0.75$) Oxidation state of Ni, Co changes from +3 to +4 during charging	Highest energy density cathode (among commercialized technologies), reduced cobalt compared to LCO	High cost, overcharging protection required (to avoid explosion), can lead to swelling in pouch type cells, requires nickel and cobalt
Li-ion (Li-rich Li_2MnO_3 composite cathodes) [1,1]	Utilizes Li_2MnO_3 as a source of Li, to form composites with LCO, LMO, NMC	High energy density, low cost	Not commercialized yet
Li-ion ($LiMn_{1.5}Ni_{0.5}O_4$ – graphite) [1,1,1]	$LiMn_{1.5}Ni_{0.5}O_4 + xC_6 \rightarrow Li_{(1-x)}Mn_{1.5}Ni_{0.5}O_4 + xLiC_6$ ($x \leq 0.8$) Oxidation state of Ni changes from +2 to +4 during charging	High voltage, high energy density, low cost	Electrolyte stability issues, not commercialized yet

TABLE III [CONT.]
COMPARISON OF DIFFERENT ELECTROCHEMICAL ENERGY STORAGE TECHNOLOGIES

Technology	Description of system	Advantages	Disadvantages
Li-ion (silicon/silicon composite-based anodes) [1,1,1]	Silicon composites are used as alloying active material as additive to graphite	High energy density, High power density	Reduced cycle life (silicon has high volume expansion on lithiation)
Li-ion ($Li_4Ti_5O_{12}$ based anodes) [1,1,1]	Lithium titanate is used as anode against any of the cathode systems mentioned above	High coulombic efficiency, high power density, ultrafast charging, exceptional safety, exceptionally long life	Low energy density (reduced voltage), higher cost per kWh
Solid state battery [1,1]	Utilizes solid state electrolyte in place of conventional liquid electrolytes	Allows use of Li metal anode à high energy density, high safety, exceptionally long life (expected)	Room temperature ionic conductivity expected to be low, Not commercialized yet
Sodium ion batteries [1,1]	Utilizes Sodium ions as charge transfer species instead of lithium	Removes dependence of lithium	Low power density expected due to slower diffusion kinetics, lower energy density, Not commercialized yet
Supercapacitors [1,1]	Electrochemical double-layer device utilizing surface charge storage	High power density, ultrafast charging, exceptional safety, exceptionally long life, uses inexpensive raw material that are abundant in nature.	Very low energy density

Applications

The applications for energy storage can be categorized based on their size of deployment into the following three categories (Figure 1): 1. Portable applications; 2. Mobility applications; 3. Stationary storage application.

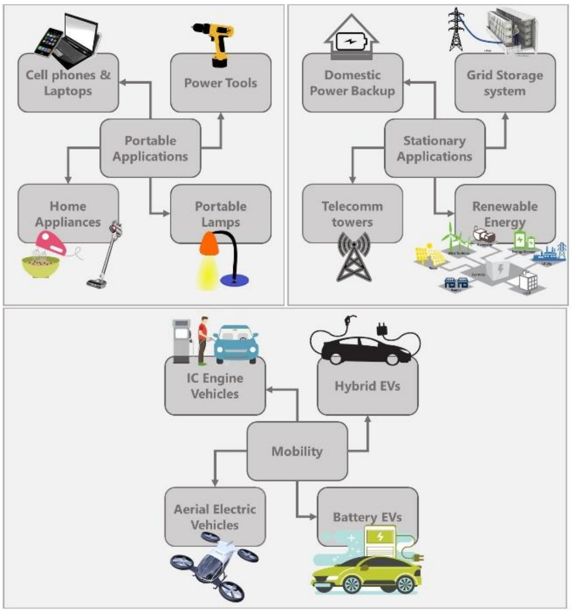

Figure 1: Energy storage applications

Portable applications have been further classified as: Power tools; Portable industrial lamps; Consumer electronics such as mobile phones, cameras, tablets, and laptops; Home appliances (such as portable vacuum cleaners, lights & fans) and toys. These applications have energy storage devices typically ranging between 10-100 Wh. These are small batteries with limited performance requirements but call for high energy density given

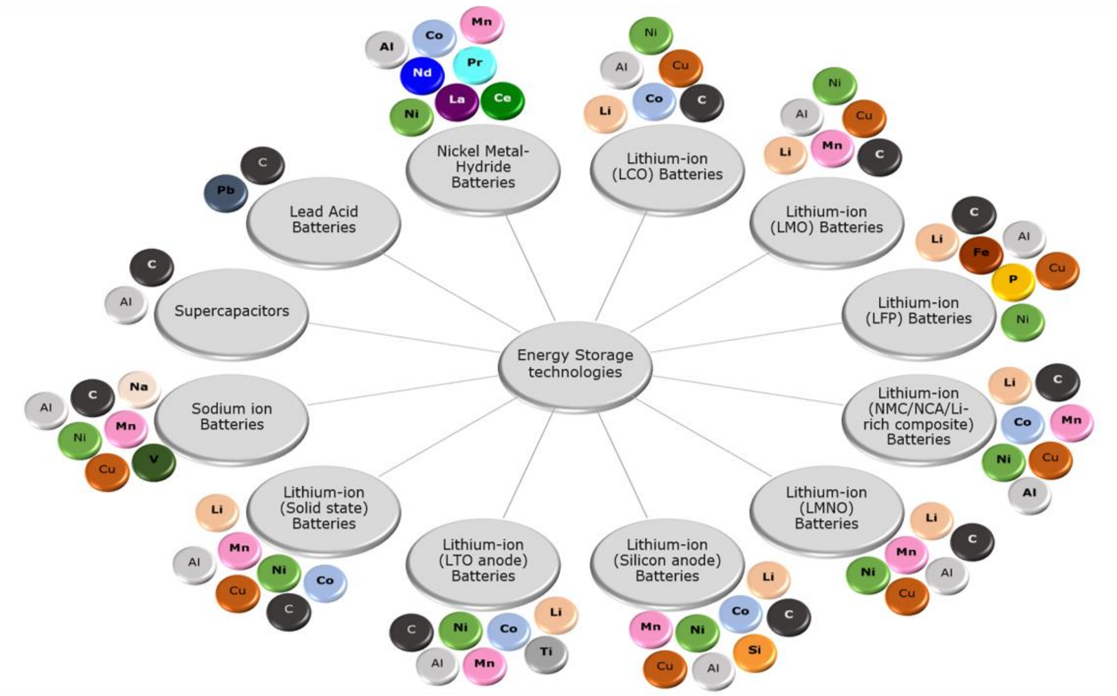

Figure.2. Elemental make-up of different electrochemical energy storage systems. The elements forming active materials are highlighted in bold text

the nature of applications. The life required of these applications is on the lower side as most of the applications get upgraded in every few years.

Mobility applications can be further classified as: Internal Combustion Engine Vehicles (ICEVs), primarily starter batteries; Hybrid Electric Vehicles (HEVs); Battery-powered Electric Vehicles (BEVs) such as electric cycles, scooters, motorcycles, 3 wheelers, cars, buses, trucks etc. Aerial Electric vehicles (AEVs) such as drones, flying taxis and passenger aircrafts. The size of batteries for this class of vehicles ranges from 250 Wh to 500 kWh. In addition, these battery solutions need to have relatively long life, robust mechanical performance and high levels of safety given the nature of the working conditions. The energy density required in these applications varies depending on the type of mobility solutions.

Stationary applications can be further classified as: Domestic power back-up; Micro grid and grid level power back-up and load levelling systems; Energy storage systems for renewable energy projects such as solar and wind farms; and power back-up for isolated, remote applications such as Telecom towers. The size of these applications ranges from 1 kWh to 100 MWh. In terms of application requirements, stationary storage applications do not have a necessity for high energy density. However, it is beneficial to have high energy density for efficient container designs. Also, wind power applications apart, most stationary storage applications do not have a requirement for high power density. Long life, low cost and high reliability are however necessary characteristics of a stationary energy storage system.

Based on the application requirements and nature of different battery technologies, the most suitable battery technologies for each application have been selected (Table IV). For example: Portable electronics such as mobile phones, tablets and laptops have an ever-increasing requirement for energy density to allow for slimmer, smaller, and lighter devices. This requirement for energy density overcomes the issue of battery cost. On adding the limitation of prismatic format to these, only LCO and low Nickel content NMC based batteries fit the bill. Technologies that are yet not commercialized at scale such as LMNO/Li-rich cathode-based Lithium-ion batteries, Sodium-ion batteries have not been discussed as potential solutions over here. However, once these technologies attain maturity, they have the potential to displace the present generation battery technologies.

Strategic analysis

India is poised to switch from an oil-based economy to an electricity-based economy. For this switchover to be sustainable, a robust infrastructure and supply chain to deliver the energy storage systems are required. Thus, apart from meeting technical requirements of applications, the choice of battery technology should also be

TABLE IV

SUITABLE APPLICATION-TECHNOLOGY FIT FOR DIFFERENT ENERGY STORAGE APPLICATIONS

Technology	Description of system	Advantages	Disadvantages
Portable applications			
Portable electronics	high energy density, moderate life	LCO, NMC (low Ni)	
Power tools	high power, high energy density, low cost	LMO	
Portable lamps	high power, high energy density, low cost	LMO	
Home appliances and toys	high energy density, moderate life, low cost	NMC (low Ni), LFP, LMO, Pb-acid	*Some versions of emergency lights/fans may work on Pb-acid batteries also*
Mobility applications			
e-cycles & robotics	high energy density, moderate power, moderate life	NMC, NCA, LMO	
ICEV starter battery	long cycle life, low cost	Pb-acid	
HEVs	high power, high cycle life	NMC (low Ni), LFP	*oversized for power delivery and life, used in float mode in a narrow DoD range*
		LTO	*subject to cost and availability*
		Supercapacitors	*Used in parallel to an energy dense battery system*

TABLE V
MINERAL RESERVES IN INDIA

Element	Indian reserve (million tonnes)	Total resource in India (million tonnes)	Chemistry used in	Comment
Lead	106	749	Pb-acid	Ore-basis; India has world's 7th largest reserve of Lead[1]
Lithium	-	-	all Li-ion	
Cobalt	-	45	LCO, NMC, NCA, Ni-MH	Ore-basis
Manganese	93	496	LMO, NMC, LMNO, Ni-MH	Ore-basis; India has 2nd largest reserves of Manganese[1]
Nickel	-	189	NMC, NCA, LMNO, Ni-MH	Ore-basis
Iron	5474	33276	LFP	Ore-basis; India has 7th largest reserve of Iron ore in the world[1]
Titanium	14	413	LTO (anode)	Mineral-basis
Graphite	8	195	all Li-ion, Pb-acid	Mineral-basis
Silicon	647	3908	Si (anode)	Quartz sand
Copper	208	1511	all Li-ion	Ore-basis
Aluminium	656	3897	all Li-ion, Ni-MH	Bauxite; India has 5th largest reserves of Bauxite in the world[1]
Vanadium	-	24	Na-ion	Ore-basis
Lanthanum	-	-	Ni-MH	No significant reserves
Praseodymium	-	-	Ni-MH	No significant reserves
Cerium	-	-	Ni-MH	No significant reserves
Neodymium	-	-	Ni-MH	No significant reserves

governed by a strategic analysis of raw materials availability in the country to prevent trading one long-term import dependency (oil) for another (batteries) and to achieve self-reliance for energy needs. This includes a study of minerals required for production of the batteries, the dependence on imports, criticality of mineral and possible substitutes. Table V shows the availability of minerals in India. India has excellent resources for Lead and there also exists a strong ecosystem for Lead-acid batteries in India. However, given its low energy density, it is not a great choice to cater to the expected boom in the mobility market. Given the lack of suitability of Ni-MH as primary choice for most applications and the lack of availability of both Nickel, Cobalt as well as rare earth elements such as Lanthanum, Cerium, Neodymium and Praseodymium in India, Ni-MH battery technology is not a good choice for the Indian market. Supercapacitors require highly specialized forms of carbon, the raw material for which is readily available and is not a concern. Thus, supercapacitors have great potential as a sustainable energy storage platform provided that the energy density can be raised to meet application requirements. Sodium-ion technology is still in early stages where the battery chemistries are not yet matured and established.

Hence, conclusions cannot be drawn regarding their strategic sustainability. When this technology matures, the import dependency of Lithium can be removed as Sodium is available in large quantities in form of sea salt (NaCl). Lastly given the application requirements, performance parameters and maturity level of technology, Lithium-ion batteries are the fore-runners to cater to most applications in the immediate future. As per the data published by Indian Bureau of Mines (2017-18), India does not have any significant

TABLE VI
AMOUNT OF REQUIRED (KG/KWH) FOR DIFFERENT LITHIUM-ION SYSTEMS. NOTE: LTO ANODE-BASED BATTERIES HAVE LITHIUM CONTRIBUTION FROM CATHODE AS WELL AS ANODE MATERIALS.

	Graphite	***Graphite + 5% Si***	***LTO****
LCO			
Li	0.15	0.15	0.40
Co	1.19	1.21	1.95
Mn	-	-	-
Ni	-	-	-
Fe	-	-	-
Ti	-	-	1.38
Graphite	0.83	0.62	0.15
Si	-	0.03	-
Copper	0.25	0.25	-
Aluminium	0.12	0.12	0.39
	Graphite	***Graphite + 5% Si***	***LTO****
LCO			
Li	0.15	0.15	0.40
Co	1.19	1.21	1.95
Mn	-	-	-
Ni	-	-	-
Fe	-	-	-
Ti	-	-	1.38
Graphite	0.83	0.62	0.15
Si	-	0.03	-
Copper	0.25	0.25	-
Aluminium	0.12	0.12	0.39
LFP			
Li	0.09	0.09	0.35
Co	-	-	-
Mn	-	-	-
Ni	-	-	-
Fe	0.69	0.70	1.23
Ti	-	-	1.68
Graphite	0.94	0.70	0.18
Si	-	0.04	-
Copper	0.28	0.28	-
Aluminium	0.14	0.14	0.48
NMC 622			
Li	0.13	0.13	0.37
Co	0.21	0.21	0.34
Mn	0.19	0.20	0.32
Ni	0.63	0.64	1.03
Fe	-	-	-
Ti	-	-	1.38
Graphite	0.83	0.62	0.15
Si	-	0.03	-
Copper	0.25	0.25	-
Aluminium	0.12	0.12	0.39

reserves of Lithium. Recently, there has been a discovery of Lithium deposits in Karnataka, India with an estimated 10,000 tonnes of ore[7]. However, this is insignificant compared to the expected requirement. With so many combinations of chemistries in the Li-ion battery family, it is necessary to understand which elements and how much of them are required in each of these combinations. Table VI shows the amount of each element required for each of the technologies. The amount of Lithium, Cobalt and Nickel required (kg/kWh) has been highlighted as these three elements present import dependencies in India.

From the point-of-view of securing raw material supplies, battery technology based on $LiMn_2O_4$ and $LiFePO_4$ are best suited as they minimize the import dependency. It is not possible to eliminate import dependency of Lithium. However, $LiMn_{1.5}Ni_{0.5}O_4$, $LiMn_2O_4$ and $LiFePO_4$ require least Lithium per kWh of energy storage and are the best choices to minimize the required import of Lithium. $LiMn_{1.5}Ni_{0.5}O_4$, when used against graphite has its cathode voltage plateau above the stability window of the conventional electrolytes and hence cannot be commercialized until advances in electrolytes allow better high voltage stability. There have been recent reports

TABLE VI [Cont.]

AMOUNT OF REQUIRED (KG/KWH) FOR DIFFERENT LITHIUM-ION SYSTEMS. NOTE: LTO ANODE-BASED BATTERIES HAVE LITHIUM CONTRIBUTION FROM CATHODE AS WELL AS ANODE MATERIALS.

	Graphite	***Graphite + 5% Si***	***LTO****
NMC811			
Li	0.10	0.10	0.33
Co	0.08	0.08	0.14
Mn	0.08	0.08	0.13
Ni	0.67	0.68	1.09
Fe	-	-	-
Ti	-	-	1.38
Graphite	0.83	0.62	0.15
Si	-	0.03	-
Copper	0.25	0.25	-
Aluminium	0.12	0.12	0.39
LMNO			
Li	0.07	0.07	0.22
Co	-	-	-
Mn	0.85	0.86	1.23
Ni	0.28	0.29	0.41
Fe	-	-	-
Ti	-	-	0.98
Graphite	0.67	0.50	0.11
Si	-	0.03	-
Copper	0.20	0.20	-
Aluminium	0.10	0.10	0.28

of $LiMn_{1.5}Ni_{0.5}O_4$ vs. LTO showing promise of better life.[8] Additionally, the order in which Li-ion chemistries are to be prioritized should not just consider the amount of lithium required, but also the life of the battery (as it directly affects the environmental sustainability of the technology). In this regard, $LiFePO_4$ outscores $LiMn_2O_4$ when used against graphite. However, LMO *vs.* LTO technology, with its promise for almost 10x longer life outscores all of them and should be preferred wherever it meets application criteria. Among available technologies, NMC 811/NCA comes 4th in terms of Lithium dependency. However, given their need for Cobalt and Nickel, these technologies should be utilized only where the high energy density is a necessity. In the future, Li_2MnO_3 based cathode chemistries should replace NMC 811/NCA technology for such applications.

Potential innovations in device design/process:

Selection of chemistry apart, device design and manufacturing process plays a major role in success of battery technologies. In terms of performance expectations, present generation batteries do not match up to upcoming applications such as electric mobility. Particularly, there is some distance to be covered when it comes to battery safety, fast charging, and battery life. Over the past decade, there have been major advancements in battery manufacturing which have led to performance improvements. However, some recent developments show major improvements arising from device design and process engineering. Some of the notable developments are as follows:

Tesla disclosed a new design technology that eliminated the welded tabs in Li-ion cell designs and instead use hundreds of contact points directly between the electrode foil and battery can, presumably based on pressure contacts. This not only simplifies manufacturing process (multiple welding steps being eliminated), but also promises significant reduction of resistive heating which allows larger cell formats, elimination of active cooling system for battery packs and achievement of longer life of batteries.[9]

Yang et al from Pennsylvania State University added heating modules in cell designs to control cell temperature while charging and discharging to achieve protocols for ultrafast charging. This was achieved by an asymmetric temperature regime in charging and discharging cycles which allowed suitable reaction and diffusion kinetics required for fast charging which are otherwise not possible at room temperature.[10]

Chen et al from University of Michigan demonstrated ultrafast charging by electrode design modification by means of laser patterning to allow better diffusion kinetics.[11]

All three cases point to major improvements as required by the EV industry without a change in chemistry, hence suggesting that there is significant potential in upgrading battery technology via design and process technology development. Along with a good product-market fit and suitable availability of raw minerals, the third important pillar on which the industry stands is technology development. As mentioned earlier, there have been some moves towards development of cutting-edge battery technology in India. However, for an indigenous battery industry to truly find its feet and grow in a market as vast as India, many more such efforts will be required.

Conclusions:

From the above analysis, the scenario of the Indian energy storage sector can be concluded as follows:

1. India has a huge upcoming market for energy storage, both in mobility and stationary storage sectors. To meet this demand, India needs a robust and sustainable energy storage industry.
2. For this industry to sustain and flourish on its own, it is critical that R&D activities in India expand rapidly.
3. In the immediate future, Lithium-ion battery technologies with Manganese and Iron-based chemistries are most suitable, keeping in mind the mineral supplies. For high energy density applications, the immediate demand can be met with low-Cobalt, Nickel-rich systems. In the future, technology development is warranted to allow Manganese based chemistries to replace the same.
4. Titanium-based anodes promise a significantly high increase in life. These should be explored for applications where they can be used. The increase in battery life more than compensates for the added Lithium import requirement due to the use of LTO.
5. Sodium-ion batteries and super-capacitors hold great potential in the future in delivering energy storage options that can eliminate import dependency.

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