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India Energy Storage Alliance

Emerging Technology Review for E-mobility

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Motivation and Objectives of this Review

The world is undergoing an immense transition in one of the most key aspects governing our lives. It is in the generation, availability and use of energy which supports all dimensions of our existence. Food production, processing and delivery, infrastructure development, clothing industry, transportation, healthcare and any other activity crucial for our sustenance depends on energy. Over time we have become used to depending on fossil fuels for providing us this key supporting ingredient. It is this core enabler, which is undergoing transition.

This transition has been made possible, in part due to the development of advanced technologies for energy storage and conversion. In this series of 4 reports, we attempt to cover all the major technologies which are either currently commercially available or those which are in the late development stages and will be commercially manufactured at scale in the next 3-5 years. All technologies for energy storage and conversion are constantly evolving and improving in performance owing to the ongoing efforts of the global academic and industrial community.

In the current report which is the first in this series of reports, we cover all the technologies which are of interest for e-mobility applications. These applications can range from small personal transportation devices such as Segways and hoverboards to heavy duty vehicles such as trucks, trains and medium sized boats.

We wish that through this report we are able to provide specific and to-the-point information to a wide range of audience who are interested in learning about these new technologies. The review is prepared keeping in mind that the readers may be from very different backgrounds and we hope that the concepts and information presented will help all decisions makers from industry as well as from the government.

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Contents

Evolution (2005 – 2015) of Battery Technology - Compactness

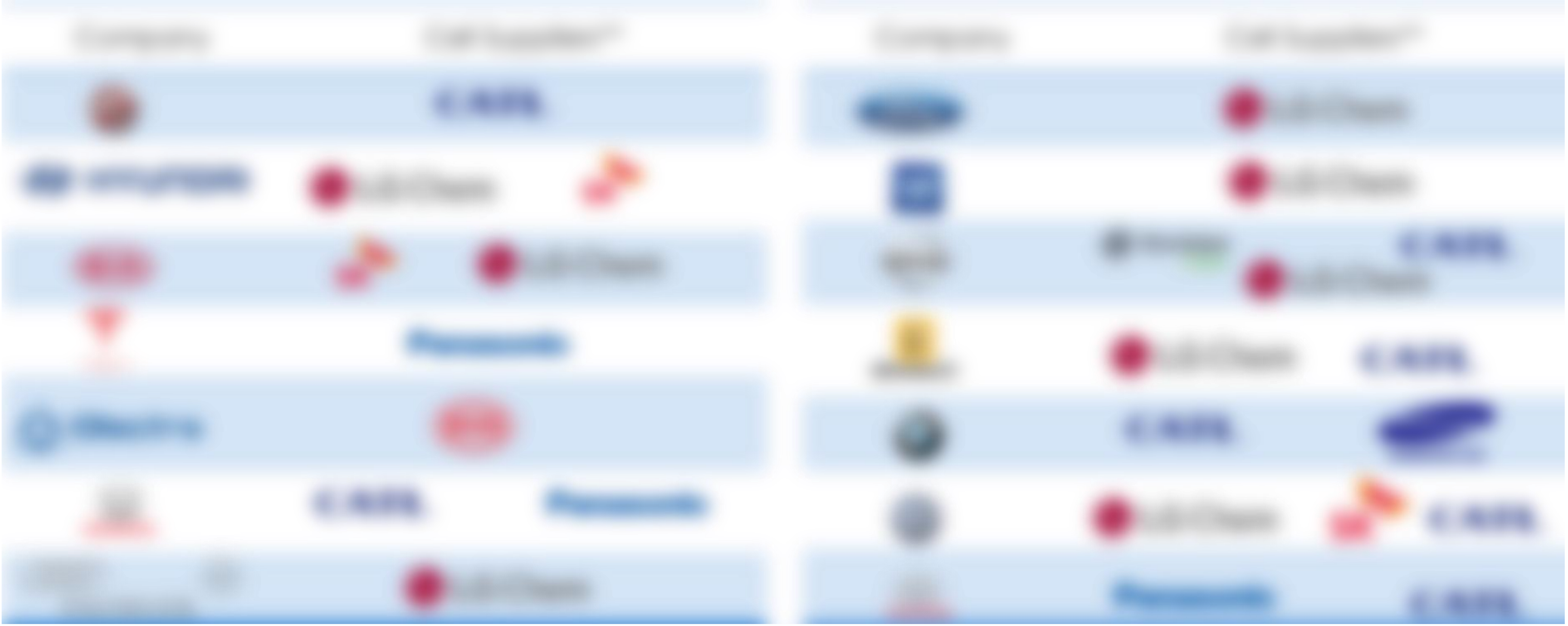
Legend which shows the effect of increasing the energy density on weight and volume reduction. A battery of same size (kWh) will weigh 10 times less if the energy density increases from 100 Wh/kg to 1000 Wh/kg.

- The **gravimetric** energy density (Wh/kg) is plotted on the horizontal axis. More lightweight storage has a higher Wh/kg.
- The **volumetric** energy density (Wh/L) is plotted on the vertical axis. More compact storage has a higher Wh/L.
- Size of the circle marker indicates year (see legend on the top left)
- All values refer to system level energy densities (not cell level). System level includes weight of all other BOP components.
- The + sign labels are cell level energy density. These are shown for Li-ion because they are used as standalone cells in some applications

Li-ion: Performance Comparison of Different Chemistries

- **LCO:** Very high specific energy, low specific power. Expensive due to Cobalt.
- **LMO:** Although moderate in overall performance but cycle life is low.
- **NMC:** Can be tailored for high power or high energy depending on the thickness of the coating. NMC has good overall performance
- **LFP:** Li-phosphate has excellent safety and long cycle life but moderate energy density. Very flat voltage profile and higher self discharge makes BMS more complex.
- **NCA:** High energy and power densities make NCA a suitable candidate for EV batteries.
- **LTO:** Cycle life and rate capability are exceptional. Low specific energy and high cost. It is the safest Li-ion battery type

Battery suppliers and car OEMs



** The list of cell suppliers is non-exhaustive

Introduction to Solid State Batteries

- All components of a traditional lithium-ion cell are solid, except the electrolyte which is a liquid
- In solid state batteries the (liquid electrolyte + separator) is replaced by a solid electrolyte making the entire battery solid. Hence the name 'solid state batteries'.

- Solid electrolytes is an umbrella term used to describe: Polymer electrolytes, Gel electrolytes or solid ceramic electrolytes
- Currently, polymer and gel electrolytes are further along in the commercialization journey (TRL = 6-7). Commercial prototypes are ready alongwith small production capacity.
- Currently, solid ceramic electrolytes are at TRL = 4-5. The prototypes are in proof-of-concept stage but not ready for pilot production.

Tatsumisago et al, Journal of Asian Ceramic Societies, 1 (2013) 17-25

Global Investments by major OEMs in SSB companies

LMP® technology in E-vehicle application

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Comparison of Fuel Cell Technologies

Parameter	PEM	SOFC	PAFC	AFC	MCFC	DMFC
Operational Life (h)	10000	15000+	8000+	8000+	10000+	-
Operating Temp (°C)	< 120	800-1000	150 - 200	< 100	600 - 700	< 100
Efficiency (%)	55 - 60	60	40	60	50	40-50
Stack power density (kW/kg)	High	Medium	Low	Low	Low	High
Stack size (kW)	0.2 - 150	1 - 1000	5 - 400	1 - 100	300 - 3000	<0.5
Applications	Stationary, Transportation, Portable	Stationary	Stationary	Stationary, Transportation	Stationary	Portable
Compatible Fuels	Hydrogen	Hydrogen, Natural gas, Biogas	Natural gas	Hydrogen	Hydrogen, Natural gas, Methane	Methanol
Electrolyte Material	Nafion	YSZ	Phosphoric acid	NaOH, KOH, LiOH	Na_2CO_3, K_2CO_3, Li_2CO_3	Nafion

- PEMFCs or Hydrogen Fuel Cells are the best choice for mobility applications among different types of fuel cells for the following three reasons:
  - Stack is very compact and lightweight
  - Operating temperature is not very high
  - Stack size is flexible and can be designed for small and heavy vehicle applications
- Other types of fuel cells such as SOFC (solid oxide fuel cells), PAFC (phosphoric acid fuel cells), AFC (alkaline fuel cells) and MCFC (molten carbonate fuel cells) are ideal for large scale stationary power generation (1- 100 MW)

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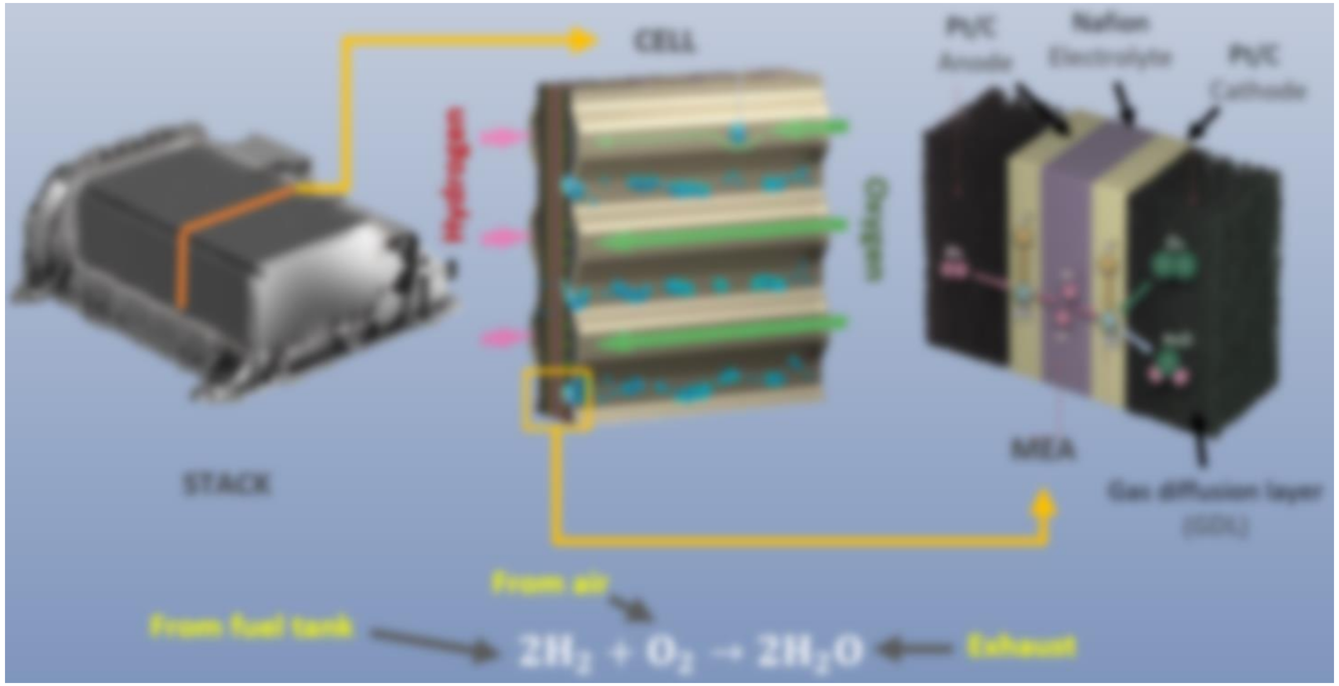
Technology Description – Fuel Cell Stack

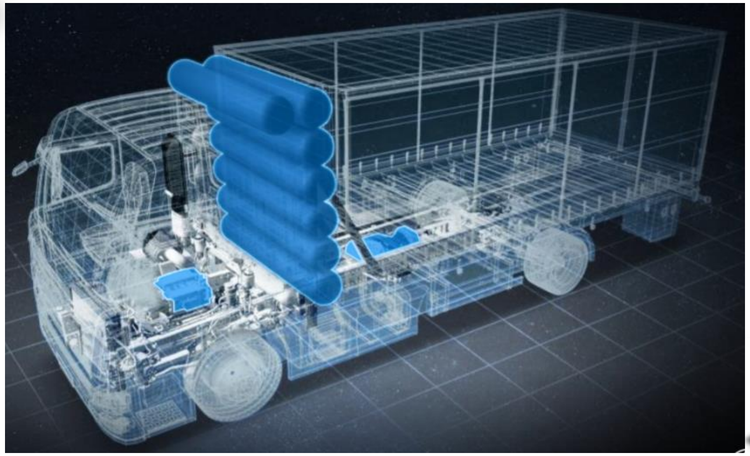


- In a PEMFC, the hydrogen from the tank reacts with the oxygen absorbed from air in the stack to generate electricity.
- **The only by-product of this reaction is water as shown in the chemical equation.**

- The design of a FC (fuel cell) system is very similar to a flow battery. There is a fuel tank, which contains the required fuel such as Hydrogen (for PEMFC) or methane, natural gas or methanol.
- The fuel flows to the stack which is the heart of the system and where the generation of electricity takes place. The oxygen required for the combustion process is acquired from the ambient air.
- The crucial difference from flow batteries or any other secondary battery is that **fuel cells are unidirectional systems.**
- This means that they are designed to consume fuel and produce electricity but not vice versa.
- Hence, a Fuel Cell is not an energy storage technology, but rather an **energy conversion device.**

Toyota Mirai – PEMFC car

Hydrogen powered Fuel Cell Buses and Trucks



Intercity Trains - PEMFC

PEMFC powered train, Germany
Cordian iLint, Alstom

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E. About the Authors

Dr. Satyajit Phadke joined CES in January 2015. His focus is on consulting services in the area of energy storage and conversion technologies for various applications such as automotive, stationary power, portable power and grid scale storage. Additionally he assists with evaluation, validation and competitive bench marking of technologies. He also heads the R&D division at CES which offers battery testing and troubleshooting services to industry clients.

Satyajit has in depth understanding of various energy storage technologies owing to his many years of involvement in the research and development of novel battery chemistry and materials for fuel cells. After completing a B.Tech from IIT Roorkee, he obtained his PhD from University of Florida in the year 2010 where his research was focused development of novel materials for hydrogen fuel cells. Thereafter he has worked on various battery chemistries as a post doctoral associate at Massachusetts Institute of Technology (MIT) and Princeton University. In 2015, he received the prestigious Le Studium Research Fellowship sponsored by the European Union to work in France on Lithium sulphur batteries for 3 years. He holds three licensed patents in the area of batteries and is the author of several technical articles in the field of energy storage.

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Dr. Tanmay Sarkar is working as senior consultant in the R&D division of Customized Energy Solutions (CES) in India. He has over 8 years of industrial experience in the field of storage technologies and also has vast knowledge about first principles-based density functional theory (DFT), material synthesis, lithium battery assembly and testing, supply chain and recycling. He has in-depth knowledge of the raw materials supply chain for battery manufacturing and is the author of many articles on Li-ion battery recycling. He completed his doctoral degree in the area of lithium-ion battery research from Council of Scientific & Industrial Research - Central Electro Chemical Research Institute (CSIR-CECRI), India. He is the author of several scientific publications and peer reviewed journals on storage technologies.