Produced by

IESA
India Energy Storage Alliance

Emerging Technology Review for Stationary Storage Technologies: Part I

Powered by

Customized Energy Solutions
Analyze · Simplify · Implement

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 final 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.

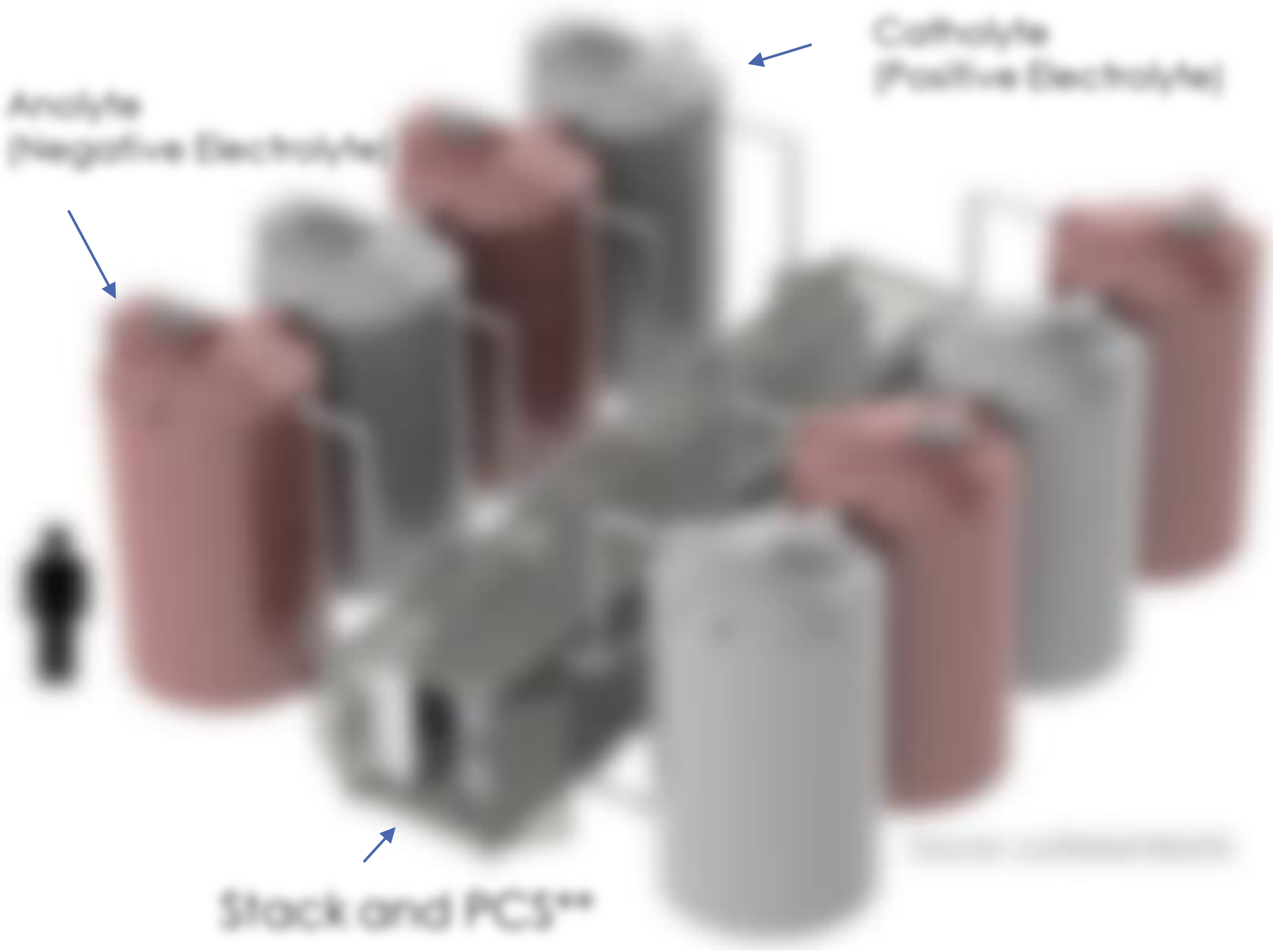
In the current report which is the 2nd in this series of reports, we cover all the technologies (except Li-ion and Advanced lead acid) which are of interest for stationary storage applications. These applications can range from small home backup systems to large grid storage installations for frequency regulation, industrial UPS systems and long duration storage of renewable energy.

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.

Dr Rahul Walawalkar
President and MD, CES India Pvt. Ltd
President, India Energy Storage Association (IESA)

Contents

Flow Battery System Design



*This system design is not applicable to hybrid redox flow batteries such as Zn-Br. In these batteries, only one tank is required since the other electrode is solid (Zn).
** Power conversion system (AC-DC bi-directional converter)

Performance Comparison: Prominent Companies

Parameter	VRB [illegible]	VRB [illegible]	[illegible]	[illegible]	[illegible]
Round Trip Efficiency	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Available C-Rates**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Depth of Discharge (DOD)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Energy Density (Wh/kg)**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Energy Density (Wh/L)**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Power Density (W/kg)**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cycle Life	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Safety (Thermal Stability***)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Initial Capital Cost ($/kWh)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Battery Chemistry*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Toxicity of Chemicals	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Maximum operating Temperature (°C)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

* System weight values not available in specification sheet. Energy and power density cannot be calculated.
** Values calculated at the system level (not cell level)
*** Flow batteries have very high thermal mass. Not very sensitive to ambient temperature variation
$ Data not provided.

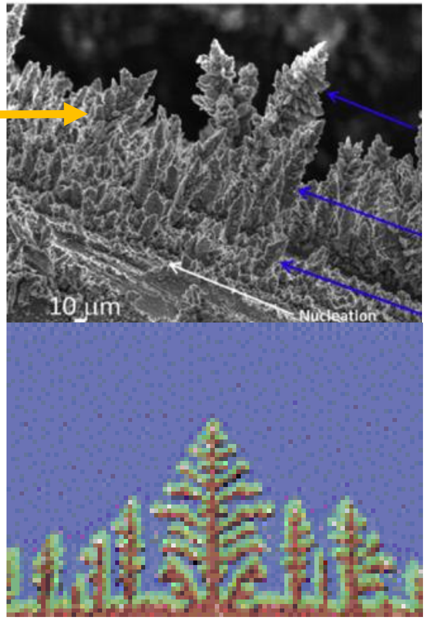
Company: NGK Insulators - Product Details

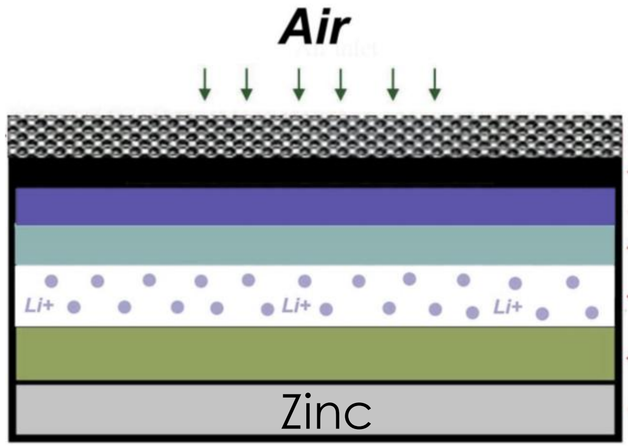
In 1919, NGK Insulators, Ltd. is established as a spin-off from Nippon Toki's Insulator Division to produce special high-voltage insulators to support the modernization of society in Japan.

- **1984** Solid electrolyte for the battery
- **1989** NAS cell and battery module
- **1997** Field tests at substations
- **2000** Field tests at customer sites
- **2002** Commercialization

Common known technical merits / challenges with Zn-air

- **Anode**: Dendrite* formation in the zinc during charging can lead to short circuit internally.
  - Different companies have developed different approaches to solve this problem.
  - Problem enhanced at higher c-rates
  - Problem is similar to Lithium dendrite formation in Lithium metal batteries ($Li-SOCl_2$, Li-S)
- **Electrolyte** is non-flammable and can operate in a wide temperature range (subzero temperatures to 45-50°C). Heat tolerance is good.
- Electrolyte components and anode and cathode materials are **very low cost**
  - Zinc, carbon, water, KOH and NaOH.
- The manufacturing process of Zn-air batteries is **NOT capex intensive**:
  - No requirement of dry room (special environmental conditions)
  - No requirement of high precision specialized equipment
  - Can reach economies of scale at small manufacturing volumes (sub GWh)
- Catalyst material in the cathode and the design of the cathode are crucial for obtaining good performance
  - **Performance metrics to consider carefully**: Cycle life, Energy efficiency and self discharge





*Dendrites is the technical term for microscopic needle like structures which form on Zinc during charging

Performance Comparison of Fuel Cell Technologies

Parameter	PEM	SOFC	PAFC	AFC	MCFC	DMFC
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Applications	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

- There are 6 types of commercially available fuel cells as listed above. PEM Fuel cells can be designed for transportation as well as stationary storage 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)
- The operating temperatures of fuel cells vary a lot. This is primarily due to the electrolyte, which is the key technological differentiator between the different types of fuel cells.

Performance Comparison of Fuel Cell Systems

practicality perspective - less component corrosion and degradation, ease of sealing and fast startup time.

**For low temperature option, Platinum is the only known option as the catalyst. At higher temperatures, inexpensive catalysts can be used.

***Electrical efficiency accounts for % conversion of fuel energy to electrical energy. Thermal energy output is not included.

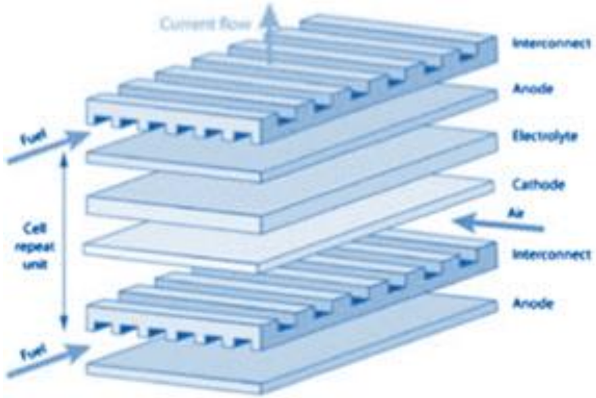
Global List of Companies Developing Fuel Cell Technology

Customized Energy Solutions

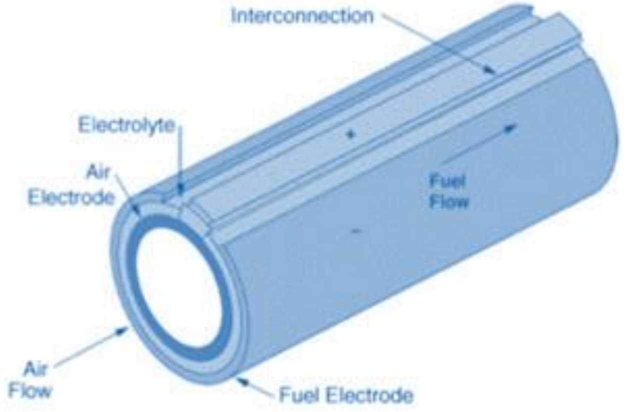
IESA India Energy Storage Alliance

SOFC Industry Progress Update

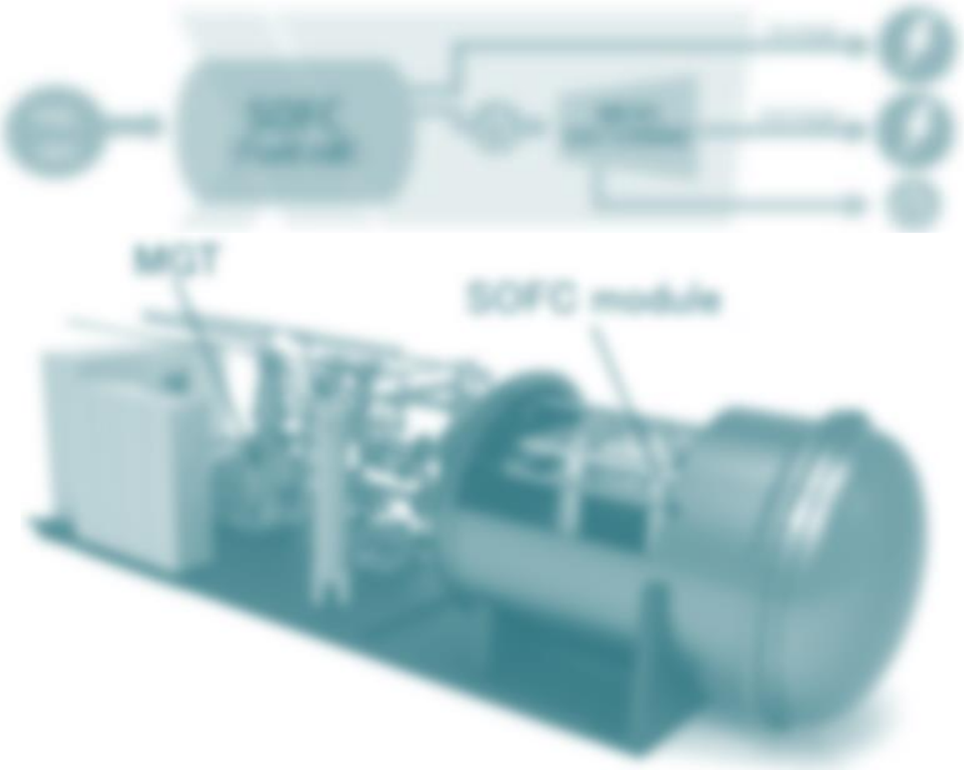
Flat plate design



Tubular design



Company 3: Mitsubishi Hitachi Power Systems (MHPS)



Home Power co-generation FC System: Viessmann/Panasonic

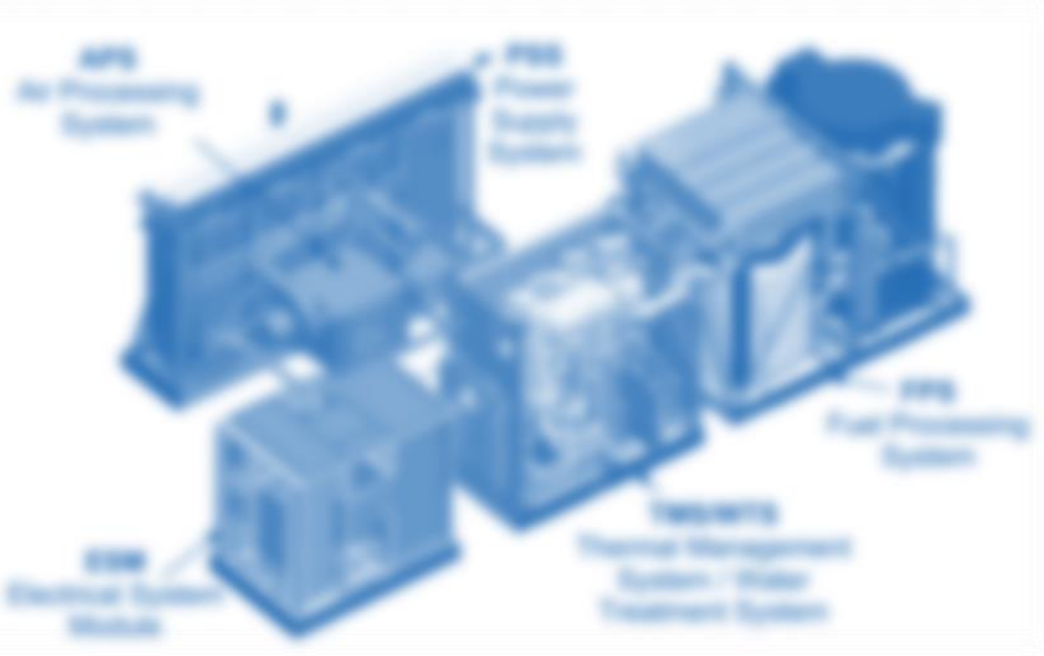
Commercially available PEMFC systems

Company	Hydrogenics			Ballard		Nuvera	Toshiba	Panasonic
Model	-	HD8	HD30	FCMove	FCveloCity	-	-	-
Continuous power (kW)	1000	8.5	31	70	100	10-100	0.7-2	0.75-1.2
Peak efficiency (%)	50	51	39	57	58	55	38	41
Operating voltage	-	20-40	108-220	230-500	337-577	-	-	-
Operating current	-	0-380	0-430	20-240	10-237	-	-	-
Mass (kg)	32000	52*	110*	250	280	-	94	197
Volume (l)	135400	41	103	413	307	-	210	730
Expected life (hrs)	80000+	10000+	10000+	20000+	20000+	-	80000	-
Application	Industrial	Auto, telecom, data center, etc					Domestic	

- Sizes of commercially available systems range from < 1 kW to 2 MW which cover the requirements of domestic as well as small industrial applications
- Modular solutions can be put together to build larger systems
- The quiet operation, small size and emission less performance (NOx, SOx and PM 2.5) makes it suitable for location much closer to the load

*Only fuel cell stack

Company Offerings



System design of a 400 kW PAFC housed in a standard shipping container.

Customized Energy Solutions

IESA India Energy Storage Alliance

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.

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. 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.

Dr Satyajit Phadke
Manager R&D
sphadke@ces-ltd.com

Dr Tanmay Sarkar
Senior Consultant
tsarkar@ces-ltd.com

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.

E. About the Authors

Mr Rajarshi Sen
Technical Advisor
rsen@ces-ltd.com

Mr Rajarshi Sen is working as a Technical Advisor at Customized Energy Solutions since 2015 in the domain of technology, projects and investment. He has 30 years of experience in the Indian renewable and energy storage market, focusing on the small wind, wind solar – hybrid and lead acid battery segment.

Before joining CES, Rajarshi Sen was the Founder Director & CEO of Luminous Renewable Energy Solutions Pvt. Ltd. during 2007-2015. He was involved in design, development and manufacturing of small wind turbines and wind – solar hybrids for global market. He has experience of developing over 500 projects across south east Asia. Also he has supplied systems to over 50 countries including markets in North America and Europe. He was also involved in setting up battery business including manufacturing and marketing at Luminous Power technologies during 2005-07.

He had prior experience with EXIDE Industries Ltd. for more than 20 years in the Industrial Batteries & Renewable Energy Division. At EXIDE, he handled industrial battery design, application engineering, production planning, marketing & distribution channels. He served as Chief Business Manager for Industrial solutions during 1996-2005. Mr Rajarshi Sen holds a Bachelor of Mechanical Engineering from Jadavpur University, Calcutta.

Acknowledgements

The authors would like to acknowledge the contribution of **Mr Calvin Raj (Junior Analyst, CES)** and **Mr Anil Jadhav (Position title, CES)** for helping with detailed research and literature survey on various topics covered in this review.