



# Emerging Technology Review for Stationary Storage Technologies: Part I

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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 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 2<sup>nd</sup> 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**

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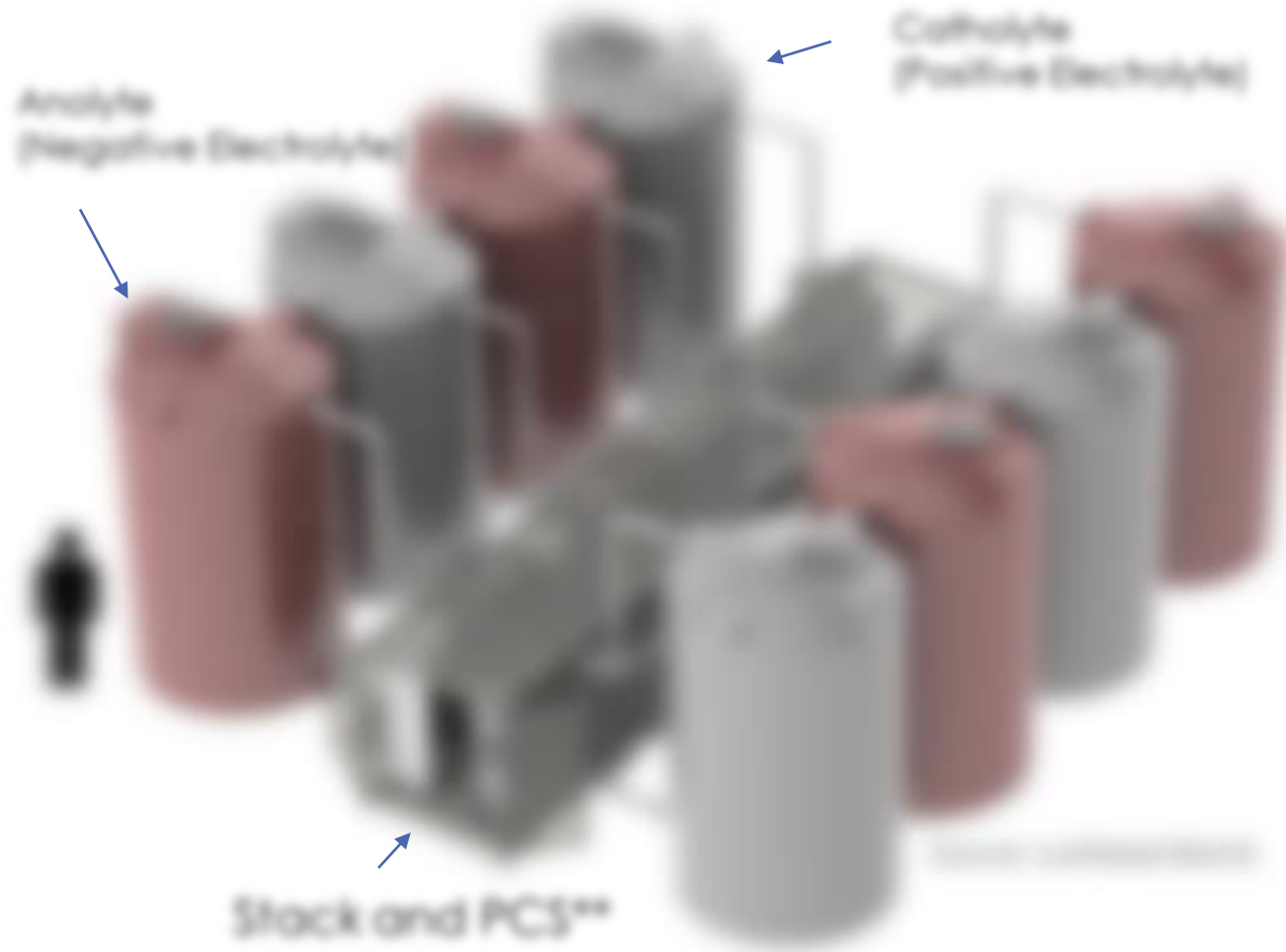
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# Flow Battery System Design



\*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)

- The design of a flow battery is intrinsically different from all other battery types. In other types of batteries, a modular unit of storage is a cell. Multiple cells form a battery pack of the desired size (kWh or MWh).
- In a flow battery, the design is completely different.
- All the energy in a flow battery is stored in its two electrolytes. These electrolytes are stored separately in two or more tanks.
- Whenever energy is required, the two electrolytes are flown through a network of pipes and pumps to reach the stack. The stack is the heart of the system where the reaction takes place and electricity is generated.
- In this sense a flow battery is much like a car engine, where the petrol or diesel is analogous to the electrolytes and the engine to the stack.
- One of the unique things about a flow battery is that the power and energy are decoupled. This is because the total energy (kWh) stored depends on the volume of the electrolytes.



# Performance Comparison: Prominent Companies

Parameter	VFB Eungye	VFB Flow	VFB V2x	Zn-Br RedFlow	Zn-Br Polaris Power
Round Trip Efficiency	70%	65-70%	65-70%	70-75%	70%
Available C-Rates**	C/4 (Power module) C/8-C/16 (Energy module)	C/4-C/16	C/4-C/8 C/2 (Power module)	C/8-C/16 (C/8 is optimum)	C/8-C/16
Depth of Discharge (DOD)	80-90%	100%	100%	100%	100%
Energy Density (Wh/kg)**	7-8	18-22 (check)	7-8	40-45	24
Energy Density (Wh/L)**	5-6	4-5	4-5	20-25	17
Power Density (W/kg)**	1-3	3-4	2-3	8-10	4-5
Cycle life	7000-8000 (estimated)	4000-7000	10000	2400-3600	-
Safety (Thermal Stability**)	High	High	High	Medium	Medium
Initial Capital Cost (\$/kWh)	300-400	300-400	400-500	750-800	1
Battery Chemistry*	Vanadium Acidic electrolyte	Vanadium Acidic electrolyte	Zn-Fe (Alkaline electrolyte)	Zn-Brine (aqueous electrolyte)	Zn-Brine
Toxicity of Chemicals	Medium	Medium	Medium	High	High
Maximum operating Temperature (°C)	40 (-20°C to 40°C)	40 (-40°C to +40°C)	40 (-10°C to 40°C)	50 (Operating range 10- 50°C)	40 (-10°C to 40°C)

\* 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.



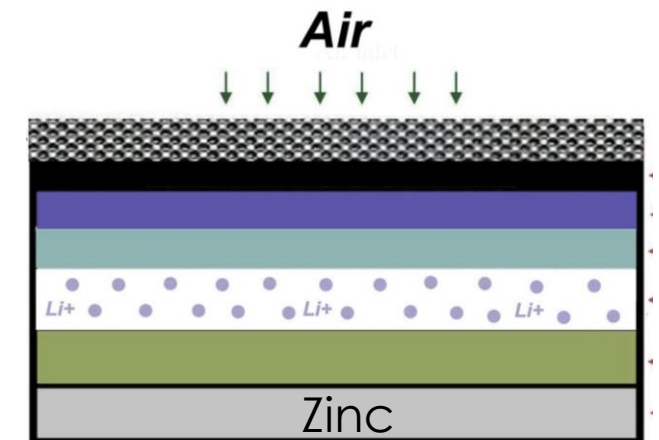
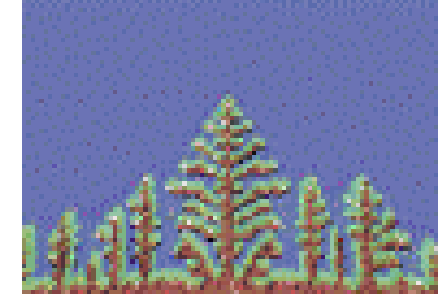
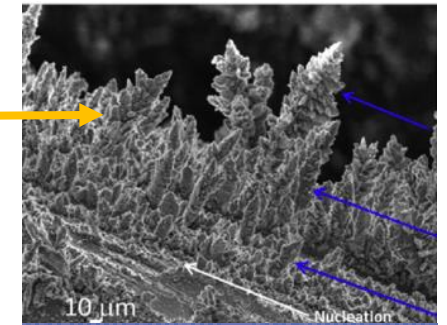
Attribute	Power
Power range	0.5 to 30 MW
Energy range	Up to 300 MWh
Specific energy density*	100 to 120 Wh/kg
Volumetric energy density*	150-170 Wh/L
Efficiency	> 85%
Reaction time	Few milliseconds
Discharge time	4-7 h
Cycle life	2000 cycles upon 90% DoD
Life duration	<15 years

NAS battery system is designed to be easily scalable to many 10s or 100s of MW



# 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<sub>2</sub>, 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
Operating temp. (°C)	100-150	1000+	800+	800+	1000+	-
Operating temp. (°C)	< 100	600-1000	150-200	< 100	600-700	< 100
Efficiency (%)	40-60	40	40	40	40-50	40-50
Start-up time (min)	High	Medium	Low	Low	Low	High
Power density (kW/kg)	0.2-1.0	1-1000	0.5-400	1-100	200-2000	<0.5
Applications	Stationary, Transportation, Portable	Stationary	Stationary	Stationary, Transportation	Stationary	Portable
Operating fuel	Hydrogen, CH <sub>4</sub>	Hydrogen, Natural gas, Biogas, CH <sub>4</sub>	Natural gas	Hydrogen	Hydrogen, Natural gas, Methane	Methanol
Electrolyte material	Water	YSZ	Phosphoric acid	KOH, KOH, CH <sub>3</sub> OH	K <sub>2</sub> CO <sub>3</sub> , Na <sub>2</sub> CO <sub>3</sub> , Li <sub>2</sub> CO <sub>3</sub>	Water

- 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



\*\*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

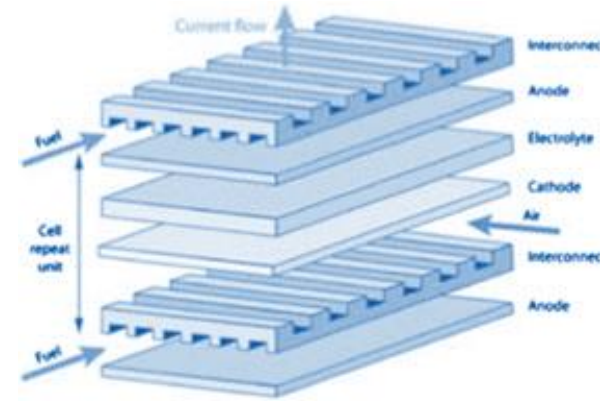


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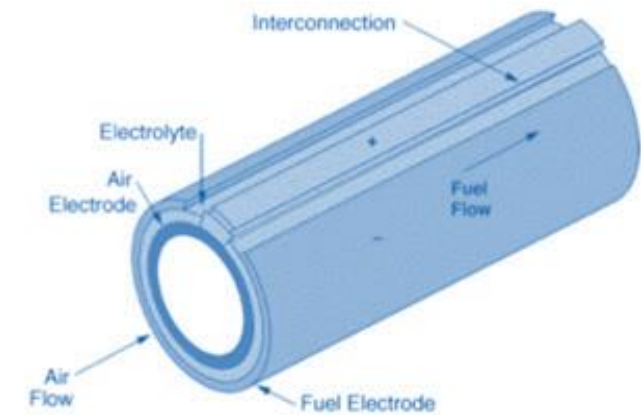
# SOFC Industry Progress Update

- The major companies developing and manufacturing this technology are Bloom Energy, Altec Energy, Mitsubishi Heavy Power Systems (MHPS), SolidPower and Redox power systems
- **Altec energy** fuel cells are deployed in North America for applications like microwave and broadband repeater towers, cathodic protection and instrumentation & control
- Until 2017, **Solid Power** had installed 1,000 units BlueGen systems. It can provide a single combined solution for small and medium enterprises with higher heat and electricity requirements than standard single-family home. This type of system can be very useful during winter seasons in places like Himachal Pradesh, Jammu and Kashmir areas in India.
- **MHPS**: In 2015, 250 kW-class SOFC-AMG prototype testing was started in Kyushu University and four other places. In 2019, the first commercial 250 kW Marunouchi Building, Tokyo, Japan
- **Bloom Energy** systems (100s of kW to few MW) have several installations globally including one in the Intel office in Bangalore.

Flat plate design



Tubular design

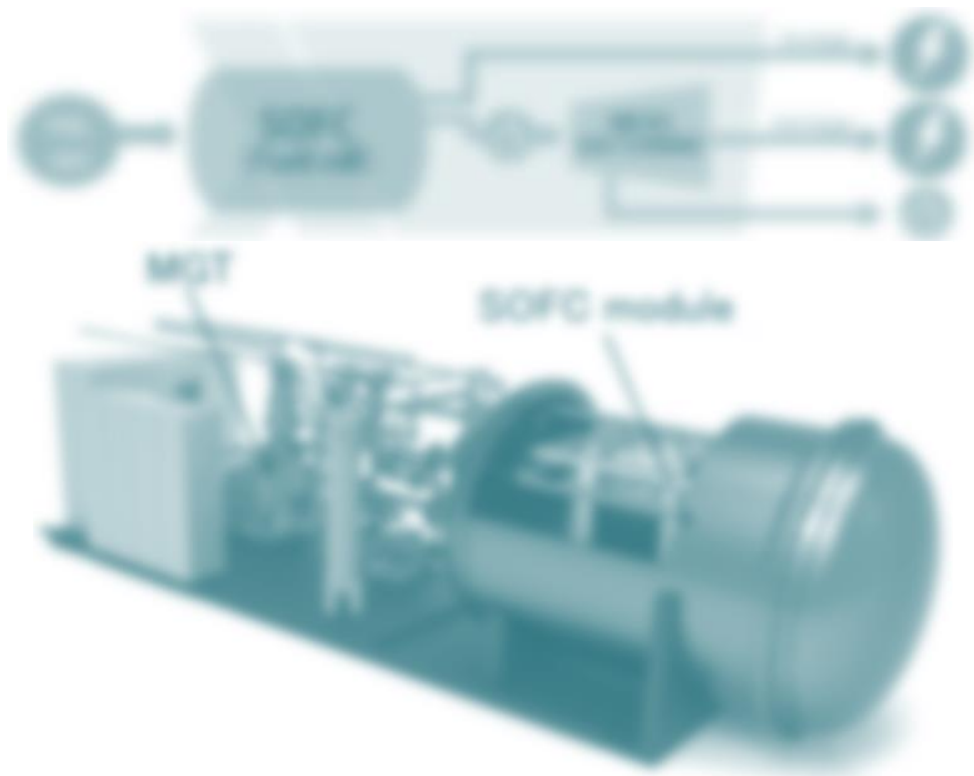


- The electrolyte used in SOFCs is solid due to which there is some flexibility in cell design. Two prominent variants of the stack are flat plate and tubular.
- Flat plate design leads to more compactness and tubular design is more robust, leak-proof and leads to better durability.
- In SOFCs, the operating temperature is high which has the following implications:
  - Disadvantages: Longer startup time, reduced lifetime due to interconnect corrosion, more expensive component materials
  - Advantages: No reformer required, no expensive catalysts like platinum, CO is not a poison for operation

# Company 3: Mitsubishi Hitachi Power Systems (MHPS)

- MHPS has developed and is testing a SOFC-MGT hybrid system. MGT = Micro gas turbine.
- The rationale for developing this system is that the exhaust from an SOFC system is available at a very high temperature. Instead of letting this heat go waste, it can be used to pre-heat gases coming into the MGT leading to higher efficiency.
- Additionally, the spent fuel stream from SOFC contains remnant unused fuel. This is also fully combusted in the MGT.
- The MGT is manufactured by Toyota Turbine and Systems Inc. MHPS has supplied the SOFC system. The SOFC-MGT hybrid system delivered to Kyushu University.
- Since the system operates at a high temperature and the MGT-SOFC have to operate in sync, it takes about 2.5 hours for the SOFC to reach full-load operation from no-load under hot conditions, and takes about 1 hour to go from full-load to no-load.

Model	280 kW-class SOFC-MGT
Rated power	280 kW
Power generation efficiency	50%
Dimensions of the unit	12.0m x 3.2m x 3.2m



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# Home Power co-generation FC System: Viessmann/Panasonic

- Home co-generation systems are designed for a typical home daily requirement in cold climatic conditions
- In many countries, LPG gas connections are provided to homes for cooking and water heating applications
- This PEMFC system runs on LPG, where the reformer converts LPG to  $\text{CO}_2$  and  $\text{H}_2$  generating a lot of heat in the process.
- The  $\text{H}_2$  is sent to the PEMFC stack where it produces electricity
- The heat is sent to a heat exchanger which heats up water for domestic uses
- The  $\text{CO}_2$  is released into the atmosphere through the exhaust

LPG is a storage cylinder for natural gas. It is a storage unit for hot water and is meant to replace a traditional hot water geyser.

<http://www.viessmann.co.uk/techinfo/techinfo.asp>

<http://www.panasonic.co.uk/techinfo/techinfo.asp>

Boiler

PEMFC



- No condensing water to waste with cold
- Long, managed run with cold water
- Low maintenance
- No noise
- No need for cold water with cold water

If heat generated by FC is not enough, the gas condensing boiler (reformer) can produce extra heat.

PEM Fuel cell stack has a power rating of 0.75 kW. During continuous operation it can generate 18 kWh in a day. After 40 h of operation, a fuel cell rest period of 2.5 h is required.

FC stack is designed for 12 years lifetime and needs maintenance every 3 years.

# Commercially available PEMFC systems

Company		Hydrogenics		Ballard		Nuvera	Toshiba	Panasonic
Model	-	H2B	H2B	FC-Move	FC-Ventury	-	-	-
Continuous power (kW)	1000	6.5	51	70	100	10-100	0.7-2	0.75-1.2
Peak efficiency (%)	30	51	39	37	38	35	38	41
Operating voltage	-	20-40	100-220	200-500	307-677	-	-	-
Operating current	-	0-380	0-430	20-240	10-207	-	-	-
Mass (kg)	32000	52*	110*	280	280	-	84	187
Volume (L)	130-400	41	100	410	307	-	210	720
Expected life (hrs)	80000+	10000+	10000+	20000+	20000+	-	80000	-
Application	Industrial	Auto, telecom, data center, etc					Domestic	

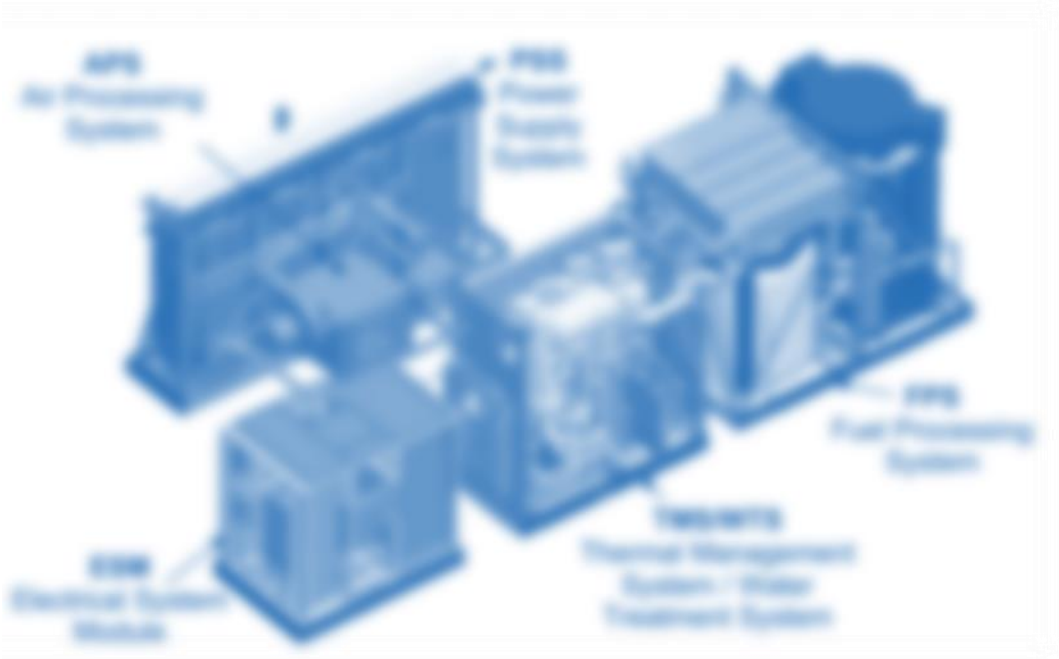
- Size of commercially available systems range from < 1 kW to 2 MW which cover the requirements of domestic as well as small industrial applications
- Modular solutions can be put together to build larger systems
- The quiet operation, small size and emissionless performance (H<sub>2</sub>O, SOx and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

\*Only fuel cell stack



# Company Offerings

PAFC manufacturer	UTC Power		Fug electric
Rated power (kW)	200	400	100
Power density (kW/m <sup>2</sup> )	2.2	4	2.4
System efficiency	90%	90%	90%
Electric efficiency	30-40%	37-40%	40-40%
System life (years)	5+	10+	10+
System weight (tonnes)	18	37	13.5
Fuel used	Natural gas	Natural gas	Hydrogen



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



- Standard systems are available in 100 kW (Fug) or 200/400 kW variations (UTC Power)
- Natural gas can be used as the fuel source which is internally reformed by the FFS to produce hydrogen (fuel)
- Electrical efficiency ranges from 30-40%. Additional 20% energy is available as heat at 121°C and 30% as heat at 60°C. Total CHP efficiency is 80-90%.
- A 200 kW system is the approx. size of a 20 foot shipping container

Each PAFC stack consists of 270 cells. Single cell voltage is 0.8 V. Total stack voltage is 216 V (DC). Source: UTC Power



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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.

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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.





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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.

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