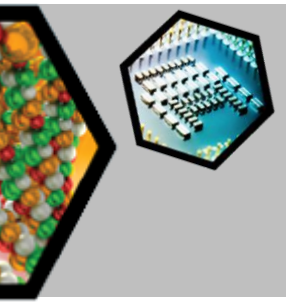
6/2/2016

SAND2016-5239PE



Molecules, Membranes, and MEAs

Jeffrey S. Nelson

Senior Manager

&

Cy Fujimoto and Mike Hibbs

Inventors

Sandia National Laboratories

Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

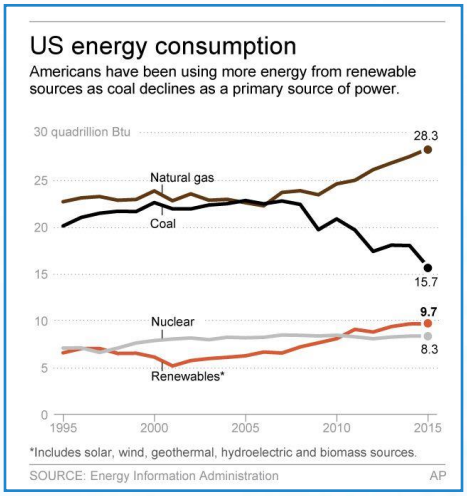
National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Markets and Technology Risk

Markets and societal drivers are accelerating the pace of adoption of low-emission vehicles and energy storage

Energy consumption is shifting to clean sources



Climate concerns are increasing

Market Risks

- **Previous startup failures**
- **Slow growth of existing companies**
- **Li-ion technology progress for utility-scale storage and electric vehicle charge times**
- **Increased NG adoption versus RE**
- **H_2 infrastructure expansion**
- **Change in political landscape**
- **Limited exits**

Increase in variable electricity sources

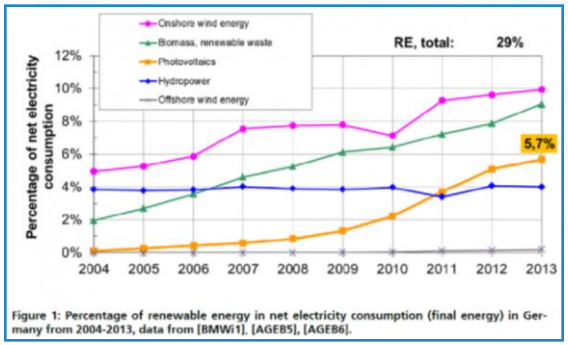
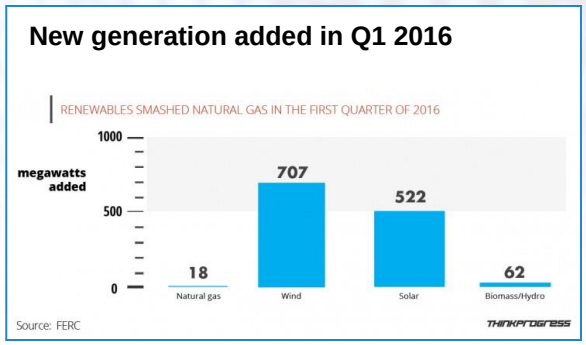


Figure 1: Percentage of renewable energy in net electricity consumption (final energy) in Germany from 2004-2013, data from [BMWi1], [AGEB5], [AGEB6].

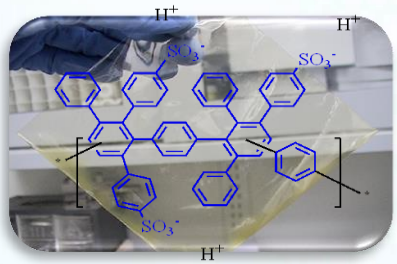


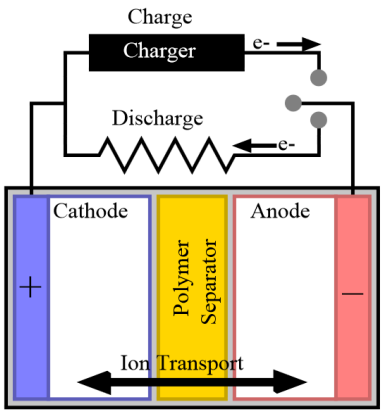
Technology and Markets

Polymer membranes play a critical role in the H_2 economy and renewable grid integration

TECHNOLOGY

Electrochemical systems produce, store, and transform energy.





Two type of membranes
Acidic: H+ transport
Alkaline: OH- transport

MARKETS

Flow Batteries for -

- Grid Support Functions
- Renewable Energy Integration

Fuel Cells for –

- Zero-Emission Vehicles (ZEV)
- Residential and Commercial Power System

Water Electrolysis for -

- H_2 for ZEV
- Storage of Renewable Energy

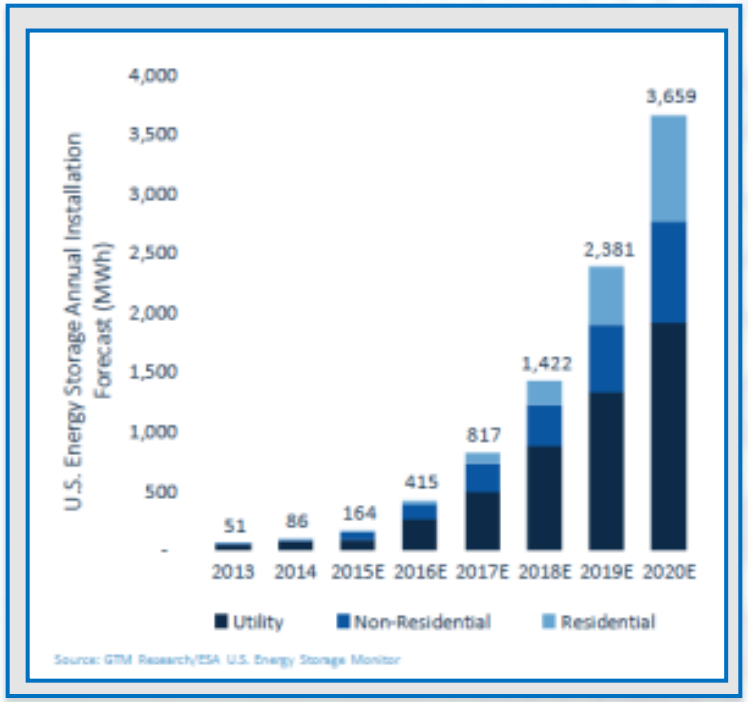
Other Applications -

- Chlorine Production
- Dielectric Separators ..

Market Size for Membranes

Much more "professional-level" market research required

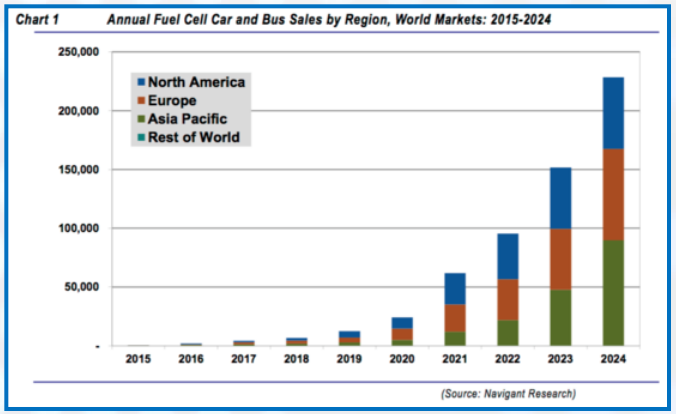
Energy Storage FB Membranes Market Forecast

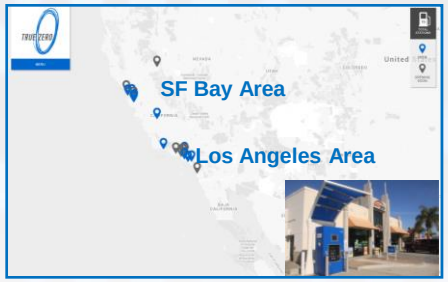


Assumptions:
$50/m^2
192 m^2/(4MWhr)
70% utility/commercial
40% GR (like early solar)

TAM FB
2020 ~ $4M
2025 ~ $20M
2030 ~ $106M

Transportation FC Membrane Market Forecast

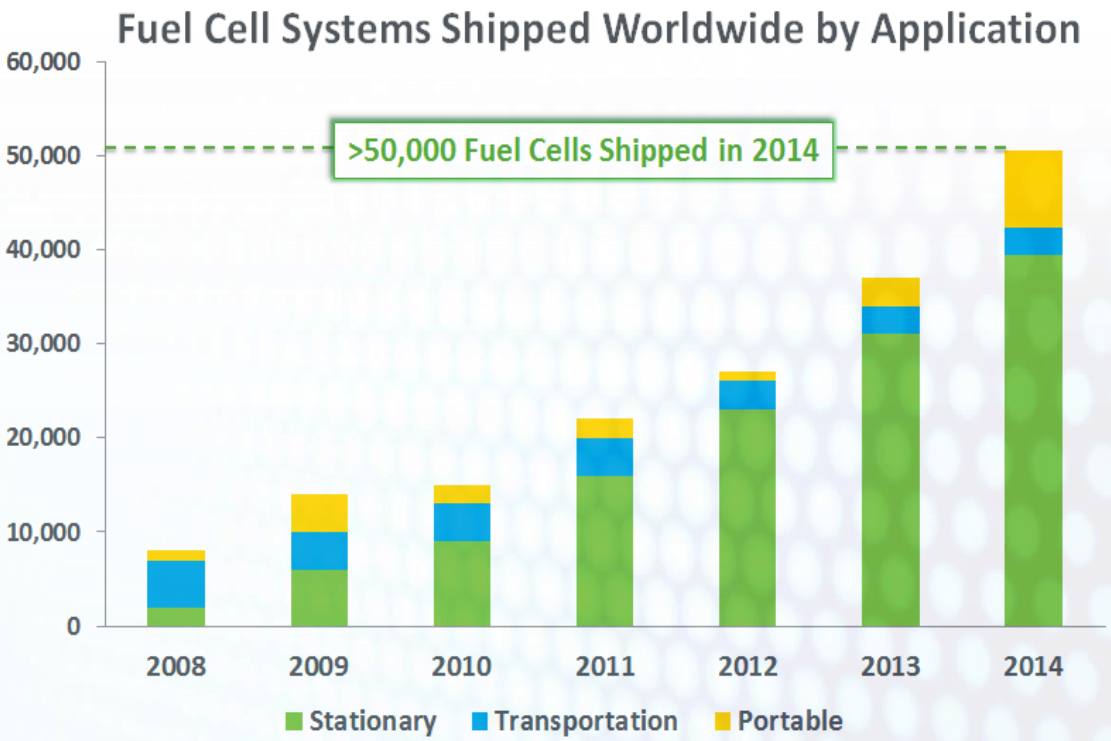


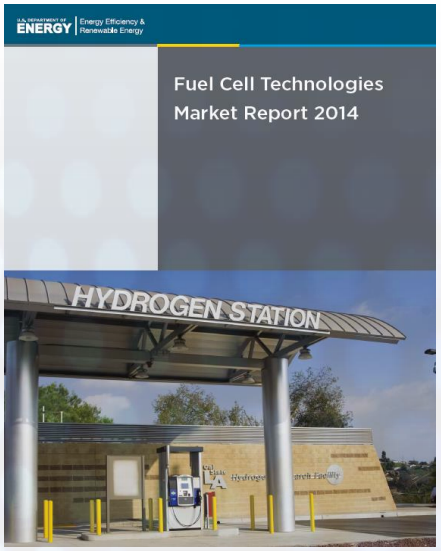


Assumptions:
$50/m^2
15 m^2/(vehicle)
50,000 Vehicles

TAM FC
2025 ~ $38M

Fuel Cells – Steady Market Growth





In 2014…

- $2B in revenues
- 180 MW fuel cells
- shipped

Consistent ~30% annual growth since 2010

Global Market Potential in 10-20 year

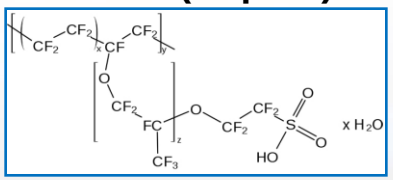
$14B – $31B/yr for stationary power
$11B /yr for portable power
$18B – $97B/yr for transportation

Competitive Advantage

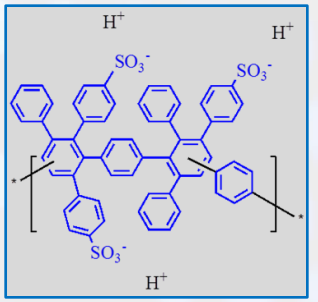
- **For acidic membranes, only one competitor technology - Nafion (Dupont) and derivatives (3M, Asahi, Gore)**
  - Our technology will accelerate market adoption (lower cost), improve performance, enable wider operating conditions, and lower maintenance costs

- **For alkaline membranes, no commercial technology meets performance and durability requirements**
  - Our technology will eliminate the need for precious metal catalysts (Pt/Ir) and reduce the cost of other system components

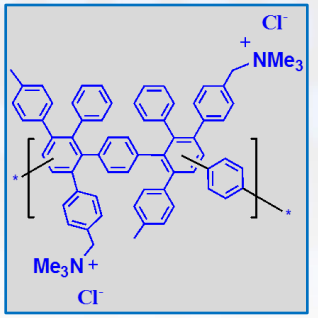
Nafion (Dupont)



Sandia Acidic



Sandia Alkaline



! Robust ~100 cm² membrane sampling to date

Competitive Advantage Examples

Sandia technology provides higher performance and lower cost

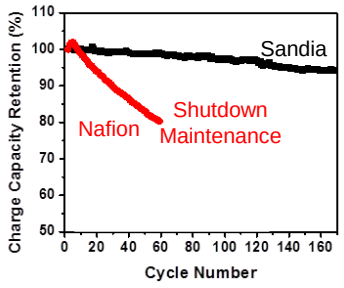
Higher performance for FB

measurements by WattJoule

	Power (mW/cm²)
Sandia	1159 (+23%)
Nafion	946

Lower maintenance for FB

measurements by Pacific Northwest NATIONAL LABORATORY



Lower Cost

Nafion > $200/m²

Sandia < $100/m²

Target cost < $50/m2

FB membrane 20-40% system cost

FC MEA Cost > 50% system cost

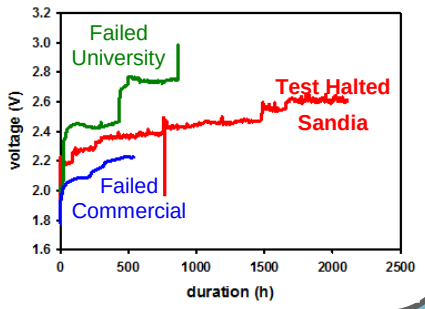
Wider operating conditions for FC

measurements by AUTOMOTIVE FUEL CELL COOPERATION

RH @ 85°C	Nafion (S/cm)	Sandia (S/cm)
30%	0.008	0.004
50%	0.019	0.022
95%	0.19	0.20

Lower cost for electrolysis

measurements by PROTON THE LEADER IN ON SITE GAS GENERATION



Value of the Innovation

- **Enabling critical component**
- **Broad market reach**
- **Strong Sandia IP portfolio**
- **Long-history in membrane R&D**
- **Prototype testing with commercial system customers**
- **Low Cap-X to establish small volume manufacturing capability**
- **National Laboratory network for analytical, performance, and durability measurements**

Alkaline Membranes

SNL has filed a provisional patent application directed to SD13741.0/S133266. The application has received serial no. 62/274,592 and a filing date of Jan. 4, 2016, “Poly(phenylene)-based anion exchange polymers and methods thereof” (KIM, YU SEUNG; LEE, KWAN-SOO; FUJIMOTO, CY).

SD12549.1/S132120 “Poly(phenylene alkylene)-based Ionomers”, Application No. 14/694,875, filed April 23, 2015 (Hibbs, Michael)

SD-10987.0/S-10090: "Poly(phenylene)-based Anion Exchange Membrane." Originator(s): HIBBS, MICHAEL; CORNELIUS, CHRISTOPHER J; FUJIMOTO, CY H. Patent no. 7,888,397

Acidic Membranes

SD13592.0/S139911 Number: FUNCTIONALIZATION OF DIELS-ALDER POLYPHENYLENE POLYMERS Application no.: 62/274569, filed January 4, 2016 (FUJIMOTO, CY).

SD12691.1/S132308: “High performance, durable polymers including poly(phenylene),” application no. 14/933,981, filed November 5, 2015 (FUJIMOTO, CY; PRATT, HARRY: ANDERSON, TRAVIS MARK)

SD-12299.0/S-129594: "Functionalization of Poly(phenylene) by the Attachment of Sidechains." Originator(s): HIBBS, MICHAEL; Patent no. 8,809,483

SD-11085/S-114236: " Multi-block sulfonated poly(phenylene) copolymer proton exchange membranes." Originator(s): FUJIMOTO, CY H.; HIBBS, MICHAEL; AMBROSINI, ANDREA. Patent No. 8,110,636

SD-7565.1/S-103422: "Sulfonated Polyphenylene Polymers." Originator(s): CORNELIUS, CHRISTOPHER J; FUJIMOTO, CY H.; HICKNER, MICHAEL A Patent No. 7,301,002.

SD-11210.0/S-116111: "Epoxy-crosslinked sulfonated poly (phenylene) copolymer proton exchange membranes." Originator(s): HIBBS, MICHAEL; FUJIMOTO, CY H.; NORMAN, KIRSTEN; HICKNER, MICHAEL A Patent No. 7,816,482.

Acknowledgements

INVENTORS:

- Dr. Cy Fujimoto, Sandia National Laboratories
- Dr. Michael Hibbs, Sandia National Laboratories

SUPPORT AND ENCOURAGEMENT:

- **Department of Energy**
  - Office of Energy Efficiency and Renewable Energy- Fuel Cell Technologies Office (Dr. Dimitrios Papageorgopoulos and Dr. Sunita Satyapal)
  - Office of Electricity Delivery and Energy Reliability- Energy Storage Program (Dr. Imre Gyuk)
  - Advanced Research Projects Agency – Energy
  - Lab-Corps Program (Dr. Dave Danielson)
- **Sandia National Laboratories**
  - Laboratory Directed Research and Development Program
- **Industry and National Laboratory Partners**
  - Los Alamos National Laboratory (Dr. Yu Seung Kim)
  - Automotive Fuel Cell Corporation (Dr. Jing Li)
  - Tom Brennan, ARCH Venture Partners
  - Many others …

Contact Information

- Dr. Jeffrey S. Nelson

Senior Manager

Semiconductor and Optical Sciences Group – 1120

Sandia National Laboratories

PO Box 5800 MS-1421

Albuquerque, NM 87185

Ph: (505) 284-1715

email: jsnelso@sandia.gov