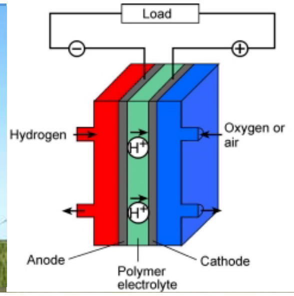
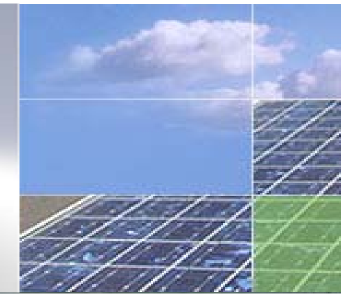
Wind



Hydrogen fuel cell

Solar thermal



Solar photovoltaic

Renewable Energy Utilization and Role of Energy Storage for Improved Reliability and Resiliency

Hashem Nehrir, Professor
Electrical & Computer Engineering Department
Montana State University, Bozeman, MT

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IEEE

Presentation Overview

- Evolution in power generation and delivery
- The increasing need for energy
- Microgrids for improved reliability and resiliency of grid
- Renewable energy utilization and need for storage/DR
- Hydrogen production and storage (future)
    - Fuel cells
    - Electrolyzers
- A vision based on which we might move forward toward a hydrogen economy

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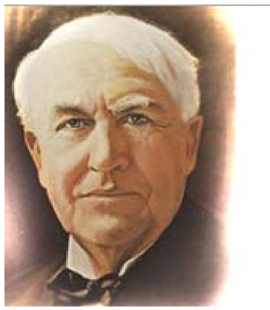
Evolution in Power Generation and Delivery: Pioneers of Electricity Generation and Transmission

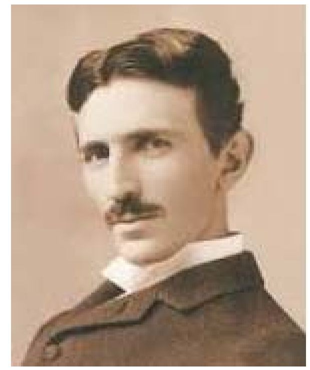
From DC DG to AC DG to Super Grid

DC distributed generation era: Incandescent light, DC power generation and transmission



Thomas Edison
1847-1931

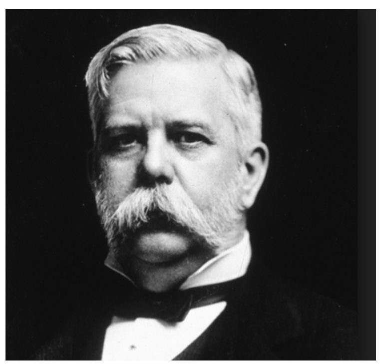
"I will make the electric light bulb so cheap that only the rich will be able to afford to burn candles." Thomas Edison



Nicola Tesla
1856-1943

Alternating current, tesla coil, transformer, induction motor, AC generation and transmission

Westinghouse helped spearhead the development of alternating current, which lead to the current super grid



George Westinghouse
1846-1914

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Human Ecology

- Human beings have always looked for better ways to obtain the supply of energy to make life safer and more comfortable. This is an irreversible path!

- For any growth rate, energy consumption will grow at a higher rate. A given fact!

- We need clean and sustainable energy sources to respond to the constant growth in energy consumption

- Most sustainable energy resources are not dispatchable

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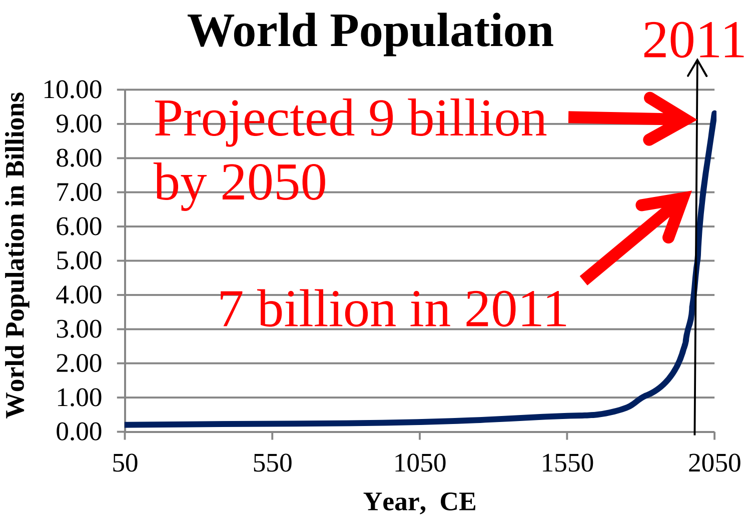
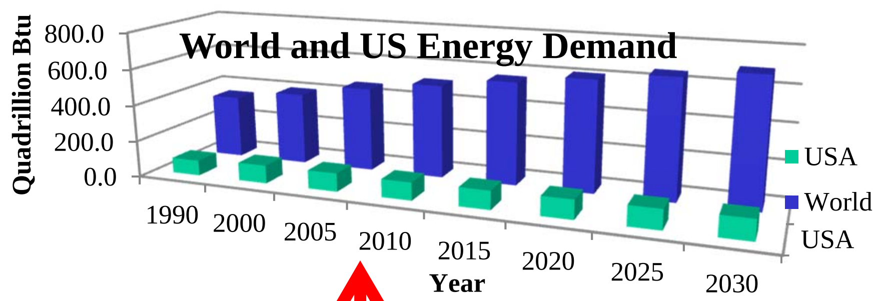
Population Growth and Demand for Electricity



United Nations compiled data shows world population growth from 50 A.D. to 2050 (projection)



Source: US Energy Information Administration, eia.gov 2011

World: About 100% growth, 1990-2030
USA: About 32% growth

- Demand for electricity keeps increasing throughout the world with population growth!
- The developing nations will represent 80% of total growth in energy production and consumption by the year 2035.

International Energy Agency (IEA)

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Super Grids and Cascading Faults

A small fault could turn into a cascading fault and cause catastrophe.

North America: The August 2003 blackout left 55 million without power.

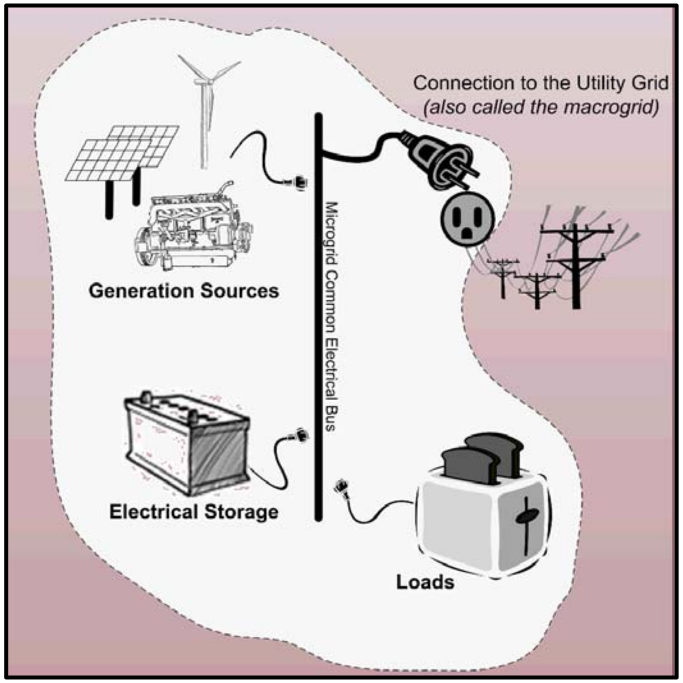
India: The July 30-31, 2012 blackout left nearly 700 million without power.

article	millions of people affected	location	date
July 2012 India blackout	670	India	30–31 July 2012
2005 Java–Bali blackout	100	Indonesia	18 Aug 2005
1999 Southern Brazil blackout	97	Brazil	11 March 1999
2009 Brazil and Paraguay blackout	87	Brazil, Paraguay	10–11 Nov 2009
Northeast blackout of 2003	55	the United States, Canada	14–15 Aug 2003
2003 Italy blackout	55	Italy, Switzerland, Austria, Slovenia, Croatia	28 Sep 2003
Northeast blackout of 1965	30	the United States, Canada	9 Nov 1965

Microgrid for Improved Reliability and Resiliency

- A microgrid is an electrical system that includes multiple loads, distributed energy resources, and storage that can operate in parallel with the broader utility grid or as an electrical island.
- The broader utility grid can be a collection of cooperating microgrids.
- According to HOMER Energy:

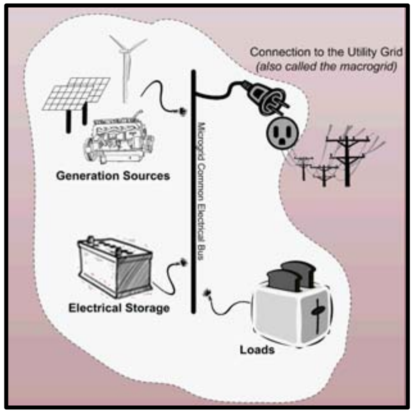
  The current global remote microgrid market exceeds $3 billion in hardware, and software sales and will grow to more than $8 billion by 2020.



HOMER Energy News, October 2013

Real-Time Microgrid Power Management – A Challenge

- Microgrids need real-time power management
- A multiobjective optimization problem
- Competing objectives, e.g.:
  - Minimize cost
  - Minimize emission



- Conventional optimization algorithms not suitable
- Artificial intelligence based multiobjective optimization algorithms play an important role in real-time operation of MGs.
  - Distributed multiagent systems – Particle swarm optimization
  - Genetic algorithm

} Biologically-inspired

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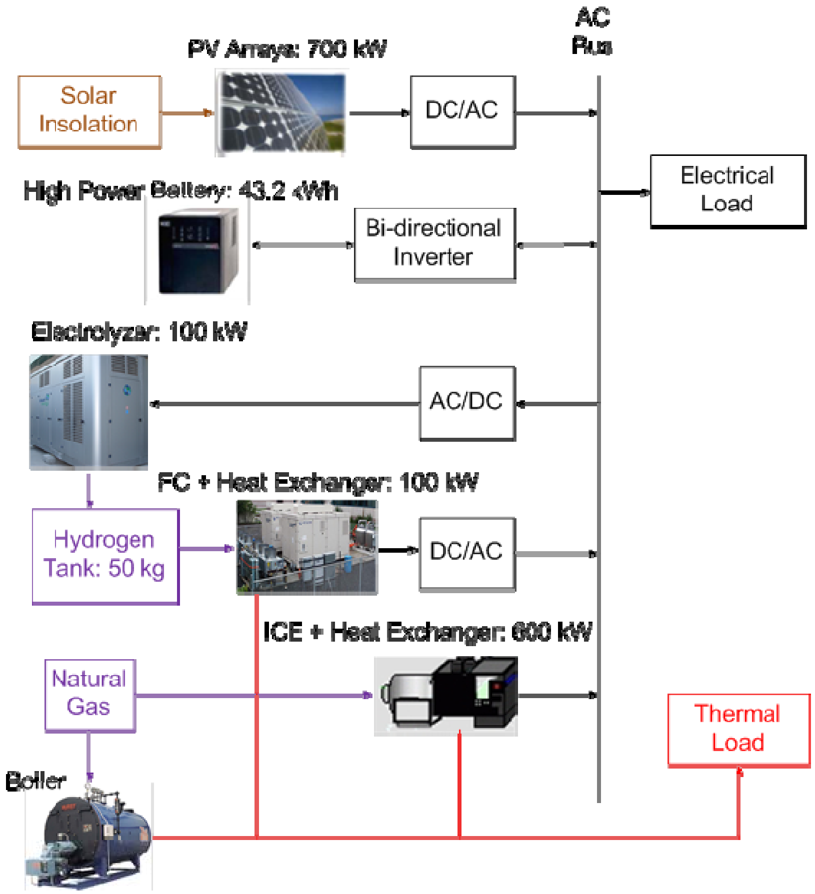
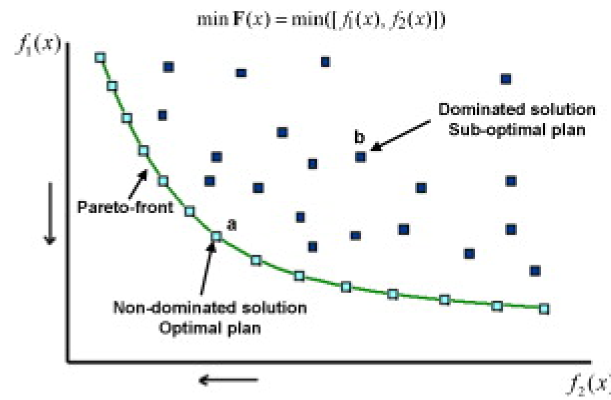
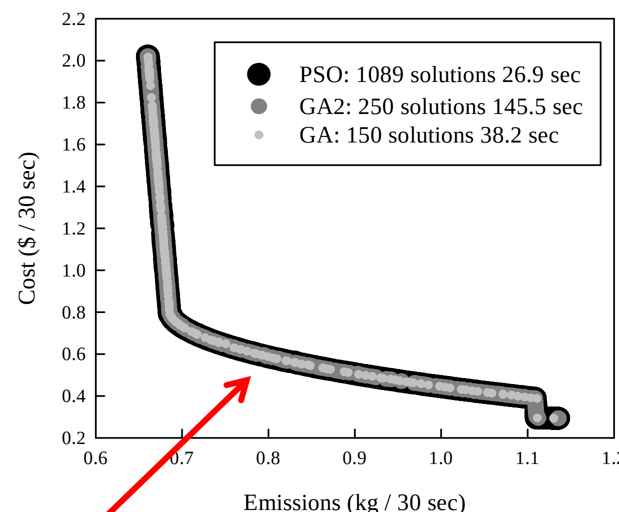
Microgrid Energy Management Using Particle Swarm Optimization



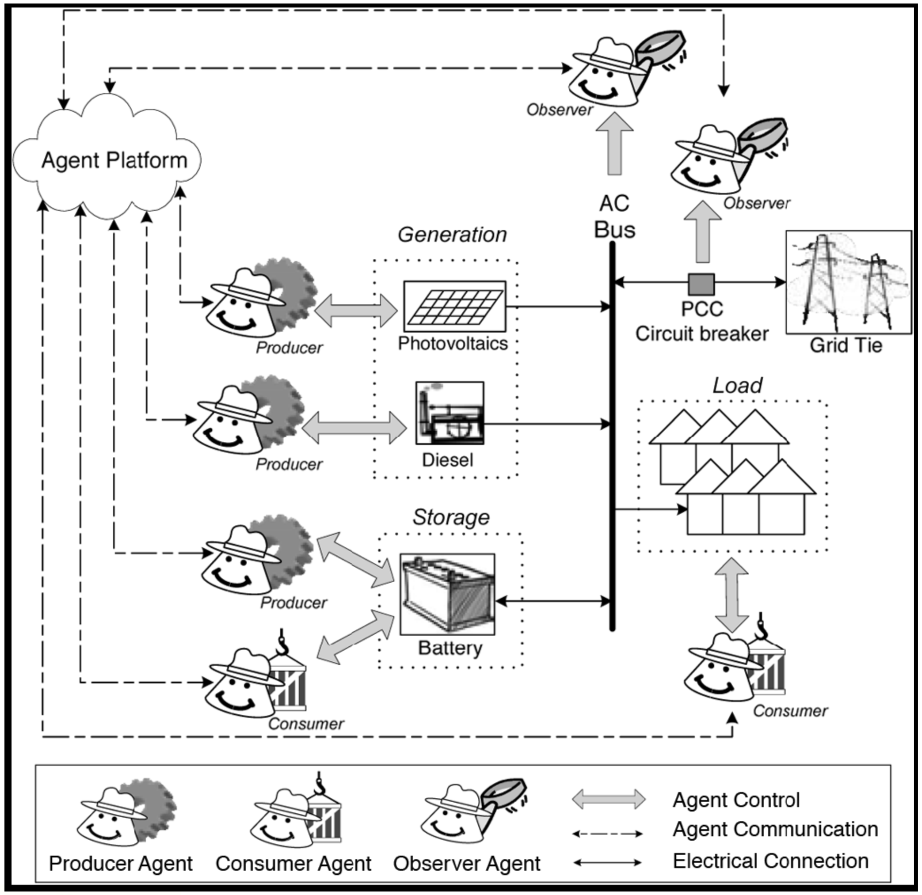
Microgrid block diagram.

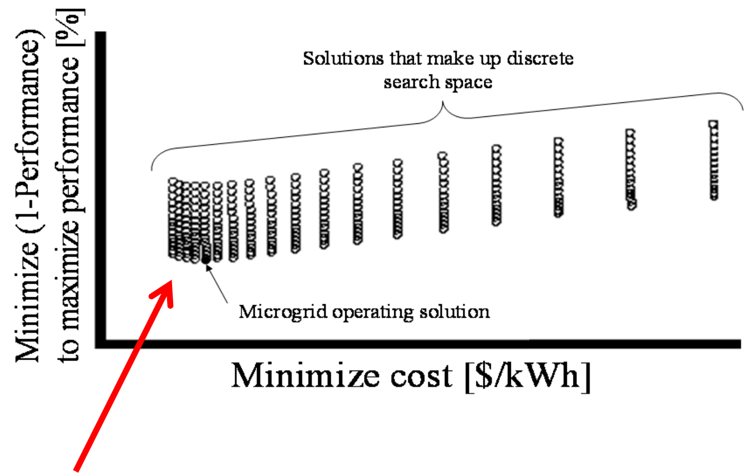




Pareto frontier

Microgrid Power Management with Distributed Agents



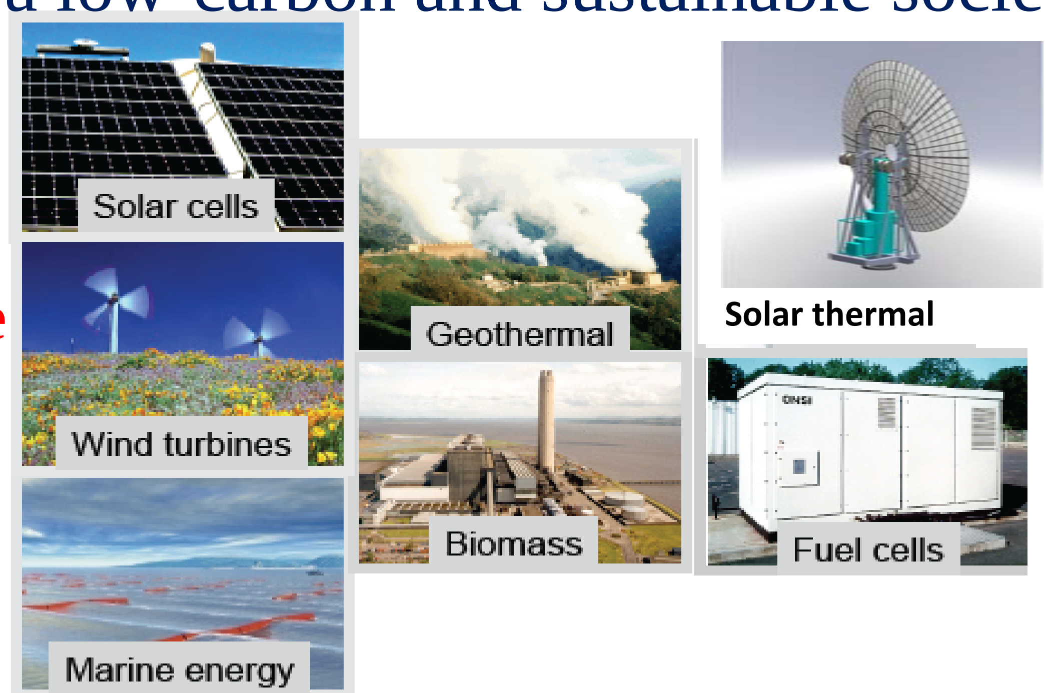


Pareto frontier

Typical Green Energy Sources for Power Generation

- Current utilization of renewable energy (excluding hydro) at the global level is around 4%.
- However, renewable energies are increasingly being introduced as alternative energy sources on a global scale toward a low-carbon and sustainable society.

Which ones of the above could be the fuel for future power generation? All?



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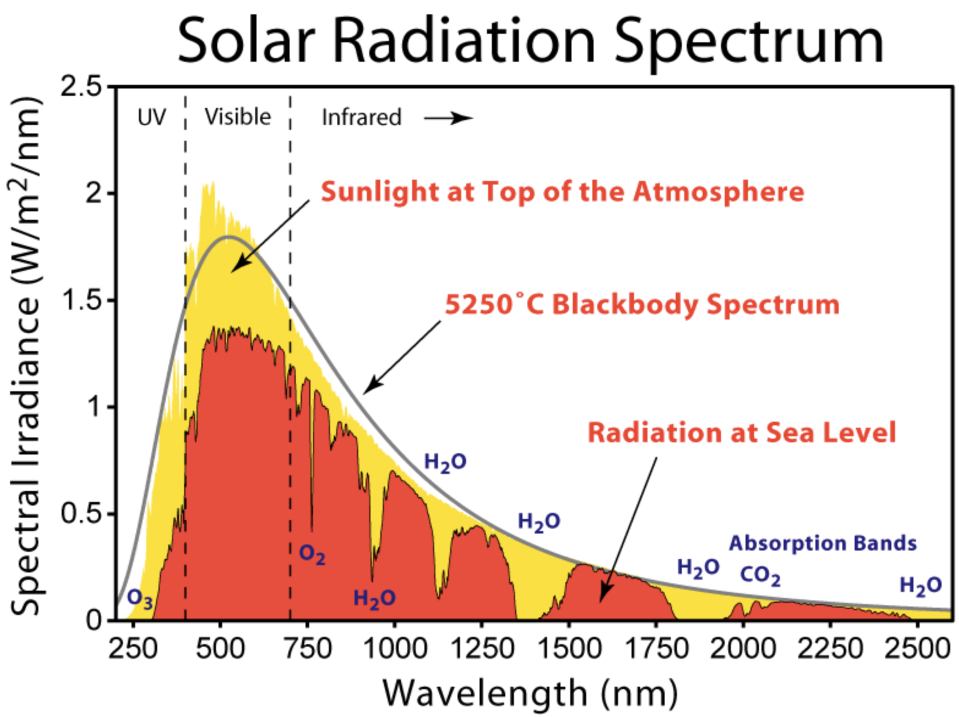
Sun as a Resource

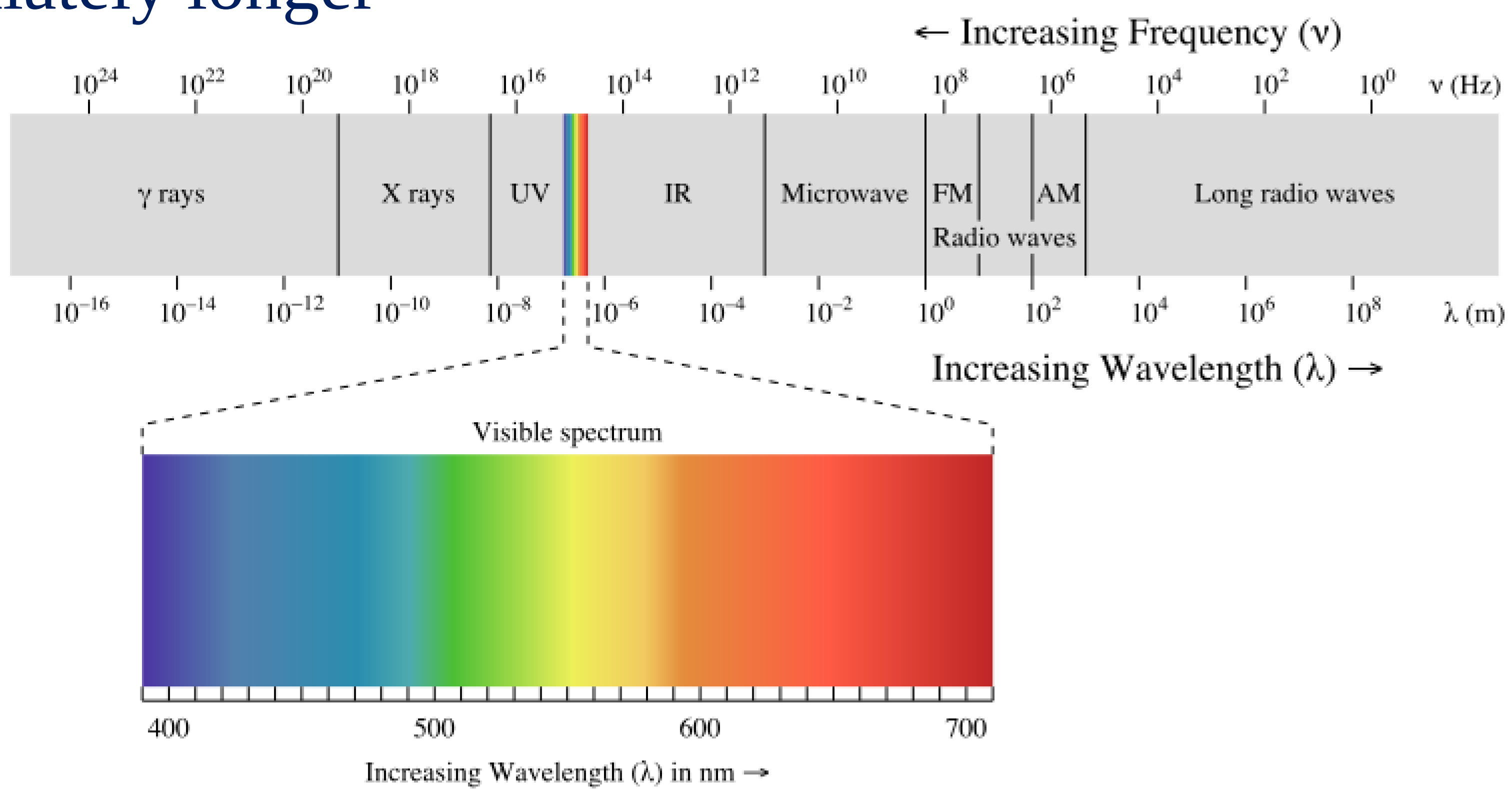
- The sun
  - 1.4 million km in diameter
  - 3.8 x 10^{20} MW of radiated electromagnetic energy
  - On average, 174 peta (10^{15}) watts of solar energy reach the surface of planet Earth continuously each day
  - About 38 % of this energy is in the visible range and can be harvested in part by solar photovoltaic arrays



Source: Wikipedia

Electromagnetic Spectrum of Solar Radiation

Visible light has a wavelength between 0.4 and 0.7 μm, with ultraviolet values immediately shorter, and infrared immediately longer



Source: en.wikipedia.org/wiki/Electromagnetic radiation

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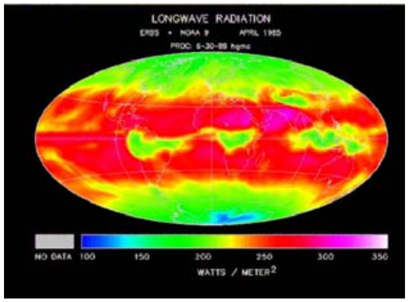
Abundant Solar Energy

- Our current world energy consumption can be met if we globally tap sunlight over only 1% of the incident area at only an energy conversion efficiency of 1%,.
- About 9% of the planet surface area is taken up by desert and efficiencies well over 1% are possible.
- Thus, exploiting massive economy of scale by establishing large arrays of solar collectors in hot desert regions of the world could open up exciting future opportunities.

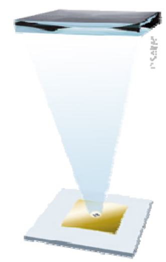
Derek Abbott, "Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs?," *Proceedings of the IEEE, Vol. 98, No. 1, 2010*



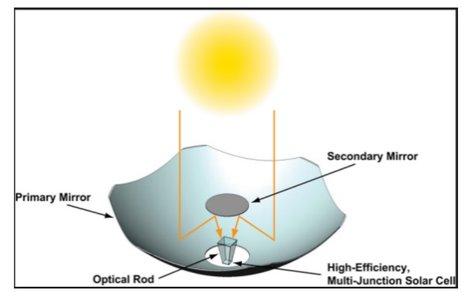
Solar Energy Conversion Technologies

- **Solar PV**

- **Concentrated PV (CPV)**
  - Focused sun beams and multi-junction solar cells



  - Optics or curved mirrors used to concentrate a large amount of sunlight onto a small area of solar PV cells



http://www.practicalenvironmentalist.com

- **Solar thermal**
  - Parabolic reflectors focus sunlight to heat water to generate steam at about 600° C to drive a turbine.

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Example Solar Thermal Power Plants

Solar thermal power plants, 9 in Mojave desert, California.

Combined capacity: 354 MW

Spain's Gemosolar thermal array, the 4th largest concentrated solar plant in the world.
Installed capacity: 19.9 MW
Source: greendiary.com

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Power Available from Renewable Sources

Energy source	Max. power	% of Tot. Solar
Total surface solar	85,000 TW	100%
Desert solar	7650 TW	9%
Ocean thermal	100 TW	0.12%
Wind	72 TW	0.08%
Geothermal	44 TW	0.05%
River hydroelectric	7 TW	0.008%
Biomass	7 TW	0.008%
Open ocean wave	7 TW	0.008%
Tidal wave	4 TW	0.003%
Coastal wave	3 TW	0.003%

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Derek Abbott, "Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs?," *Proceedings of the IEEE, Vol. 98, No. 1, 2010*

Renewable Energy Utilization and Need for Storage

- The introduction of variable renewables is one of the primary drivers behind renewed interest in energy storage.
- Hybrid systems and energy storage can play an important role in making the RE-based power smooth/stable.
- Mandate from the California Energy Commission: 1300 MW storage by 2020.
- Technological breakthroughs are needed for electric energy storage.

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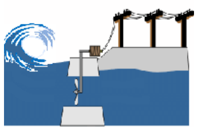
Variety of RE-Based Power Generation and Storage Technologies

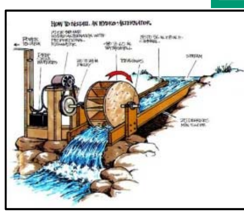
Wind

Solar

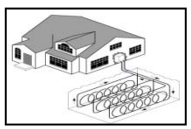


Tidal

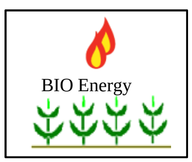
Micro-hydro



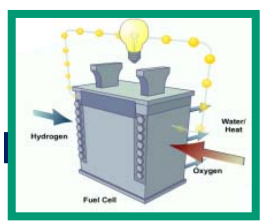
Geothermal

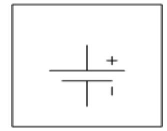


Bio-Energy



Hydrogen Fuel cell

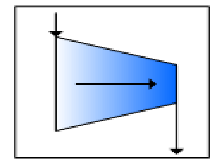




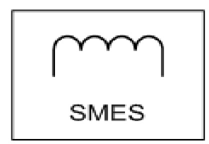
High Power and high capacity Battery

Super-Cap

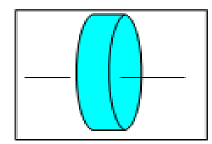
Pumped hydro



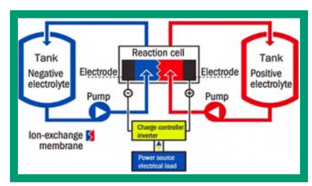
Compressed air energy storage



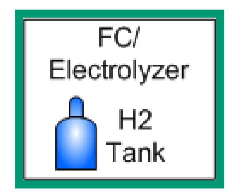
SMES



Flywheel



Flow battery



H2 Storage

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Energy Storage Types and Technologies

- Storage types
  - Fast-acting (access-oriented): Power capacity
  - Slow-acting (capacity-oriented): energy capacity

Storage Class	storage technology
Access-oriented (high power)	Supercapacitor SMES Flywheel High-power battery
Capacity-oriented (high energy)	High-energy flow battery Hydrogen energy storage

Cannot have everywhere:

- Compressed air energy storage
- Pumped hydro

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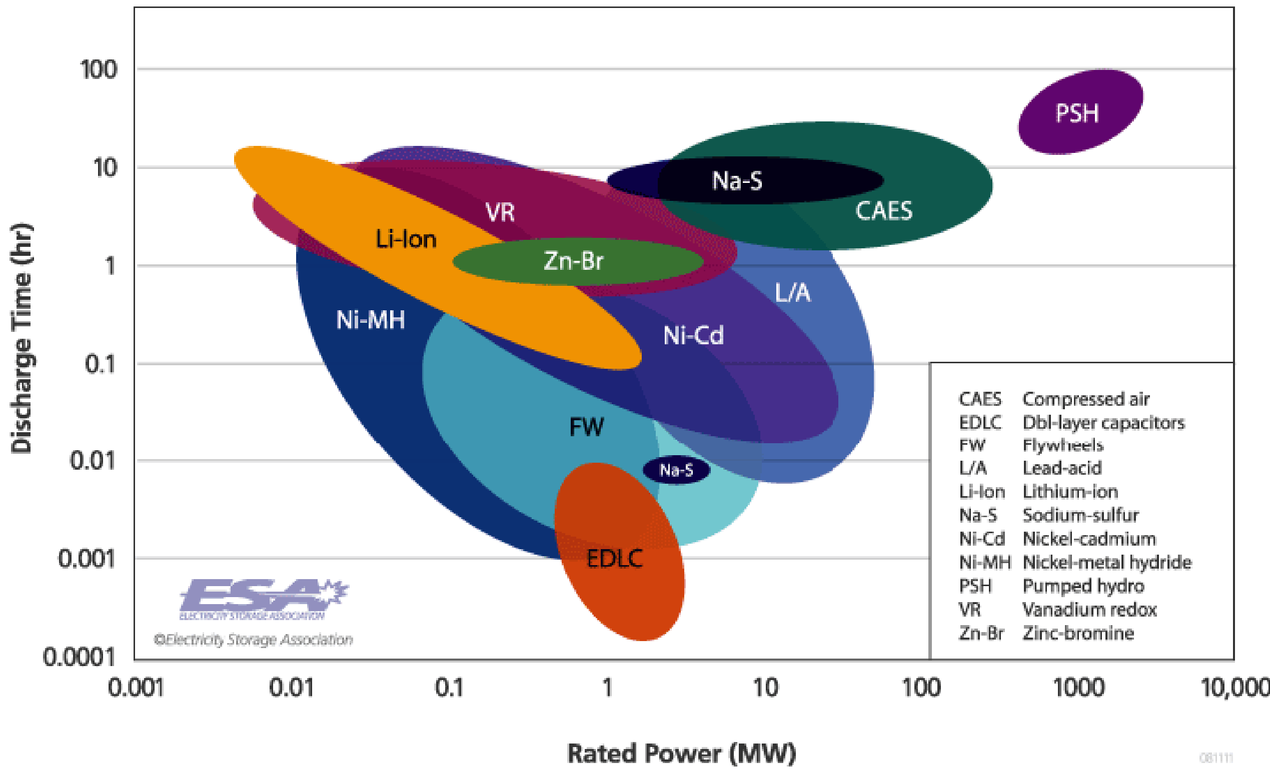
Storage Types, Rating and Discharge Time



Technical Report **NREL/TP-6A2-47187 January 2010, available at** :
NREL.GOV

- Lead acid
- Lithium-ion
- Nickel-Cadmium
- Nickel-metal-hydride
- Sodium-sulfur
- Polymer-based storage
  - Flow batteries - grid/microgrid-scale
  - Fuel cell-electrolyzer

Presently, high cost of new batteries is a big obstacle in their widespread use.

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Flow batteries: Types and Principle of Operation

- Vanadium redox flow batteries(RFB) .
- Zinc-bromide flow batteries (ZBFB).
- Other chemistries are under development.
- Operation is based on ion exchange, similar to fuel cells.
- Power and energy capacity of flow batteries can be designed independently. – Increased cell area increases power capacity and increased volume of electrolyte solution increases energy capacity.

- **Flow batteries have the potential to even out the fluctuations in large-scale variable renewable-based power generation.**

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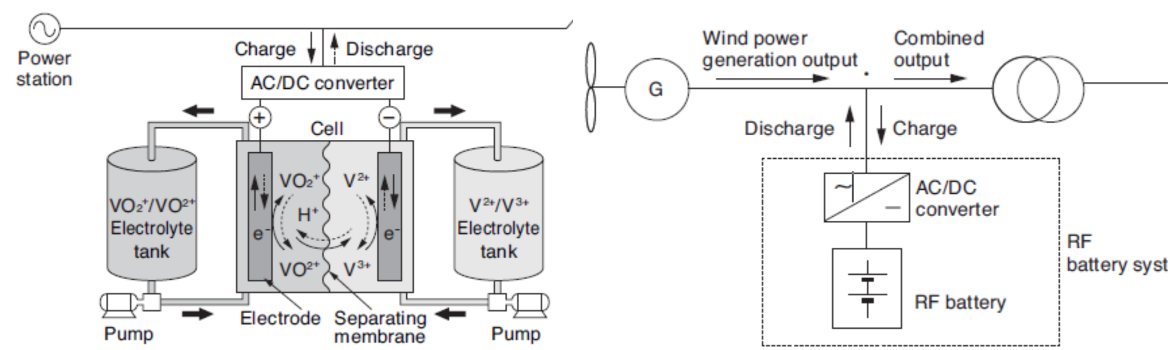
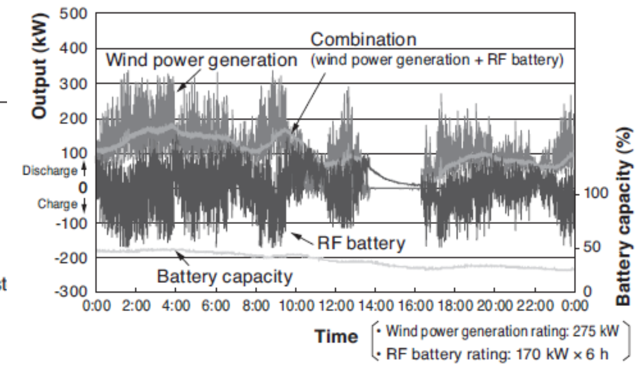
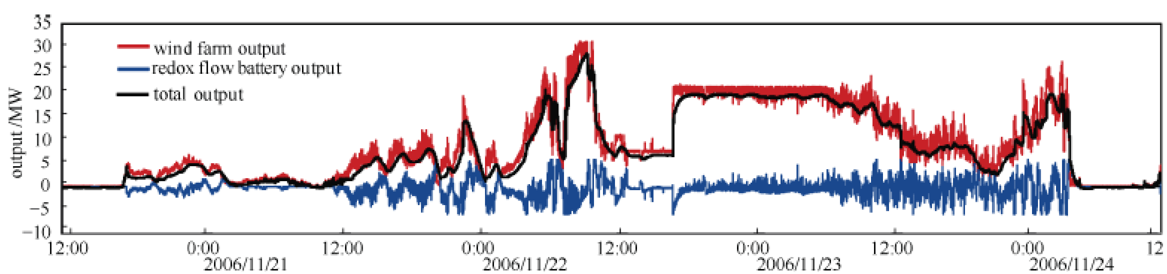
Redox Flow Batteries for Stabilizing Output Power of Wind Farms



Principle of operation and configuration of RF battery

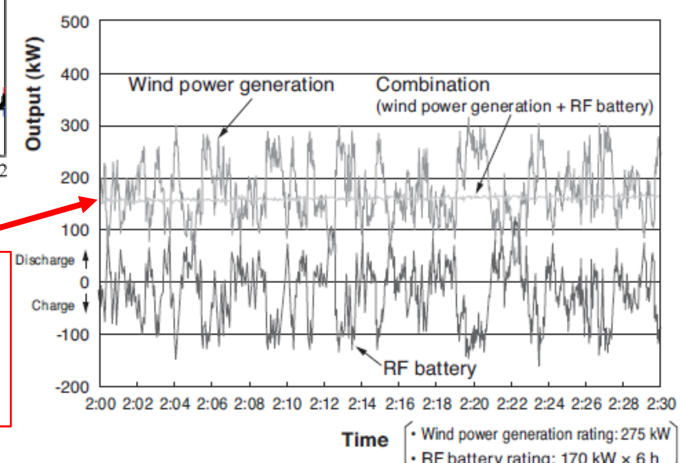


Wind power stabilization with an RF battery bank, 24 hours –1-hour battery time constant.
275 kW windfarm, 170 kW x 6h RFB.



Sumitomo Electric industries (Japan).
Wind power stabilization with an RF battery bank – Battery capacity too small for the wind farm. 30-minute battery time constant. 30.6 MW wind farm, 6 MWh RFB.

Combined wind power and RF battery



Second by second wind power stabilization with an RF battery bank – long battery time constant (1 hour).

Hokkaido Electric Power Co. will invest in a 60 MWh RFB from Sumitomo Electric Industries Ltd. to bolster its grid capacity.
The Nikkei reports, July 7, 2013

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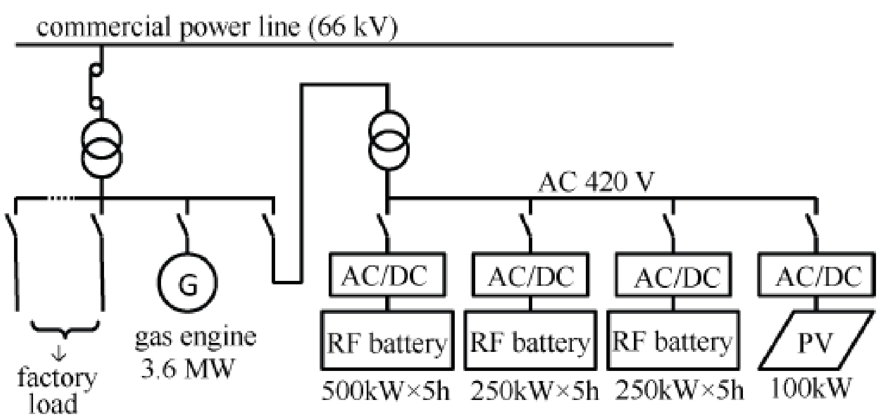
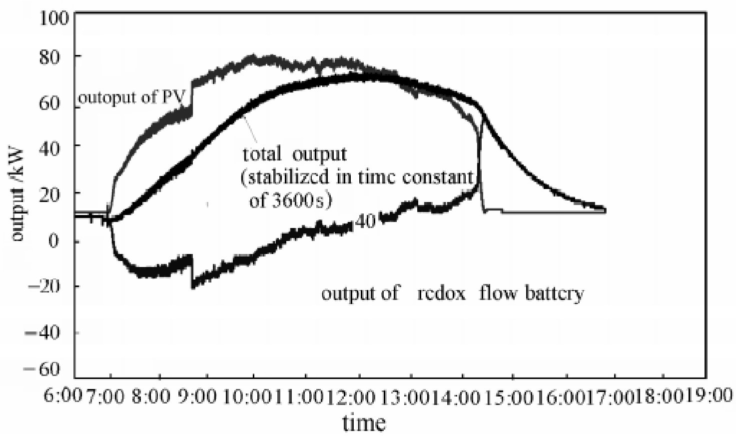
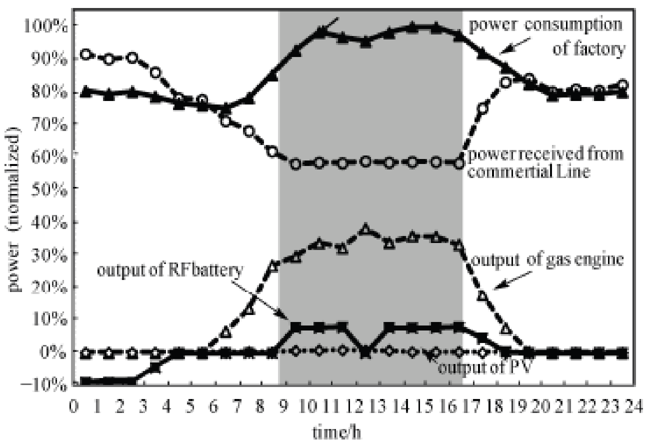
RFB for Stabilizing PV Output Power and for Peak-load Shaving



Arial view of the 5-MWh RFB and 100-kW PV.



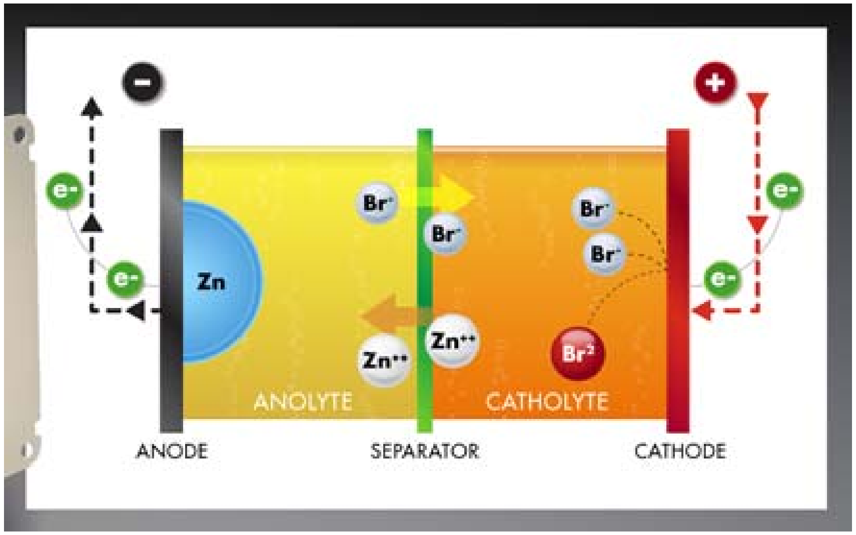
RFB stabilized output power.

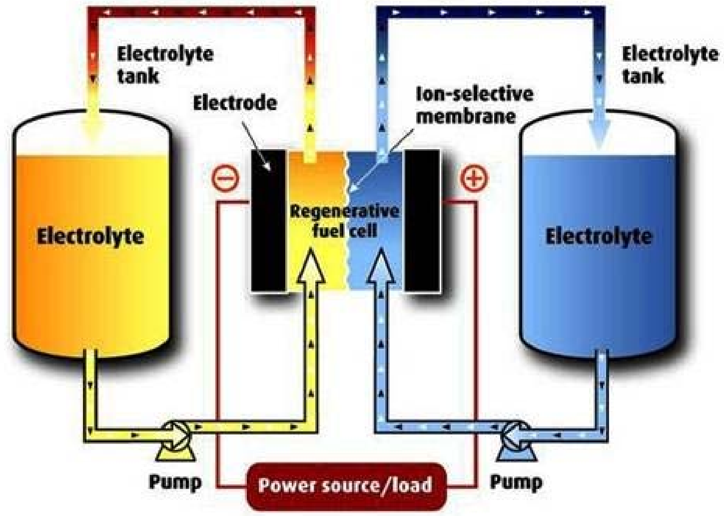


RFB for peak load shaving

Yokohama Industries, Japan (test in 2012)

Zinc Bromide Flow Batteries





ZBB Energy Corp., in Menomonee Falls, Wis., USA
Premium Power Corp., in North Reading, Mass., USA

Small-scale for Microgrid applications
25 kW, 50 kWh
http://www.zbbenergy.com
USA

Photo: ZBB Technologies

Backup Power. Batteries with flowing electrolytes could be key to smoothing out intermittent wind and solar power.

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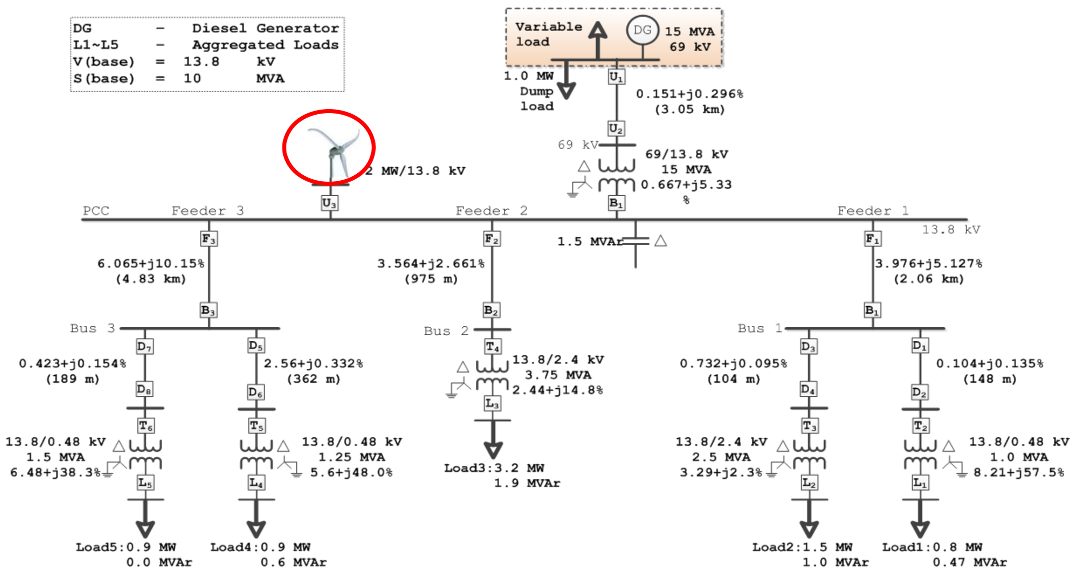
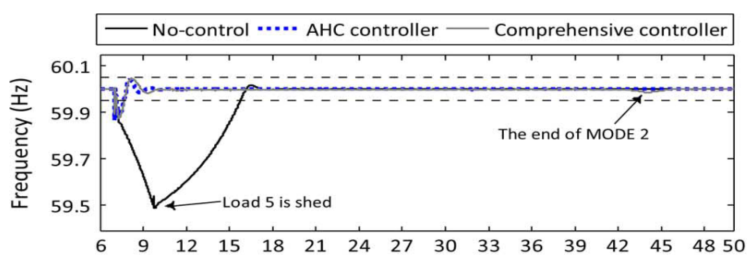
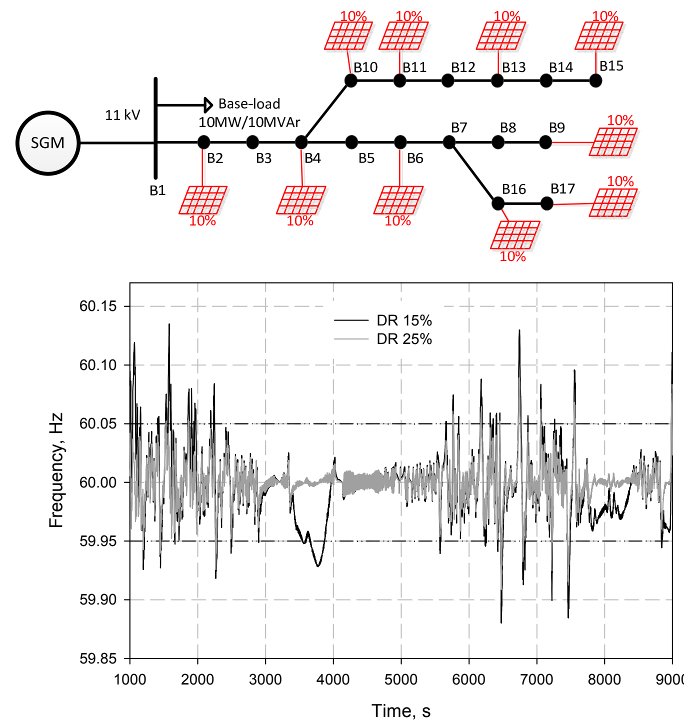
Reducing the Need for Storage Batteries by Using Demand Response

Demand response can be used for power management and for ancillary services (e.g., frequency regulation).





System frequency: Unexpected shortage in wind power generation.



System frequency response with 25% PV penetration.

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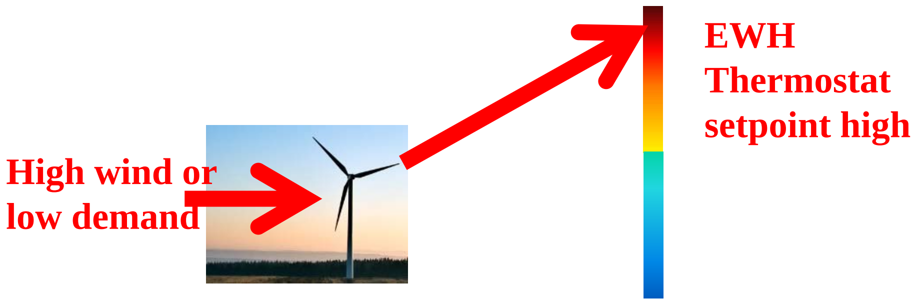
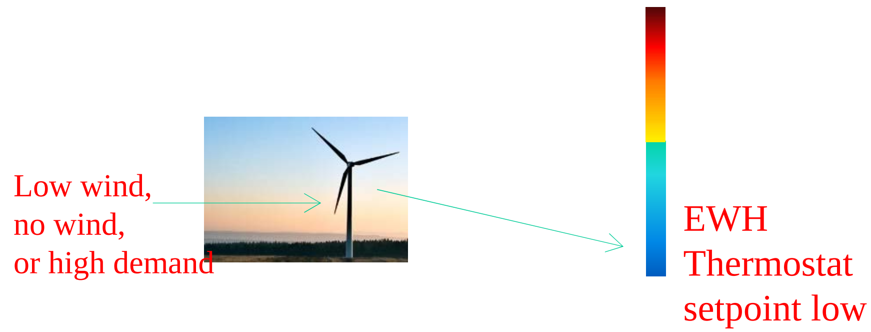
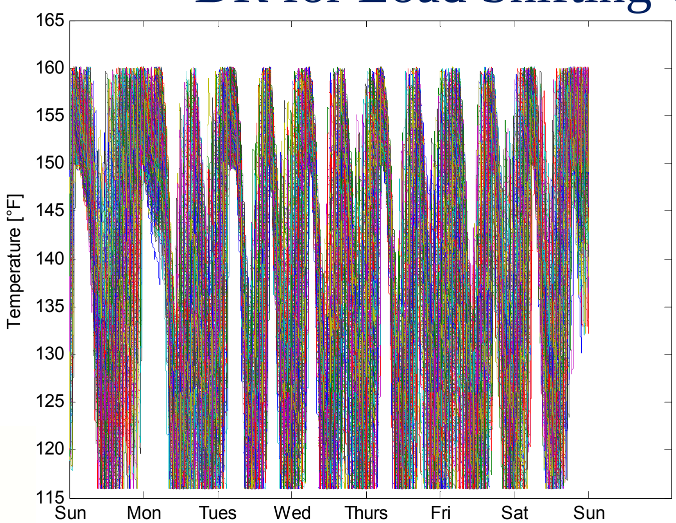
DR Using Electric Water Heater Thermostat Setpoint Control

DR for Balancing Wind Generation

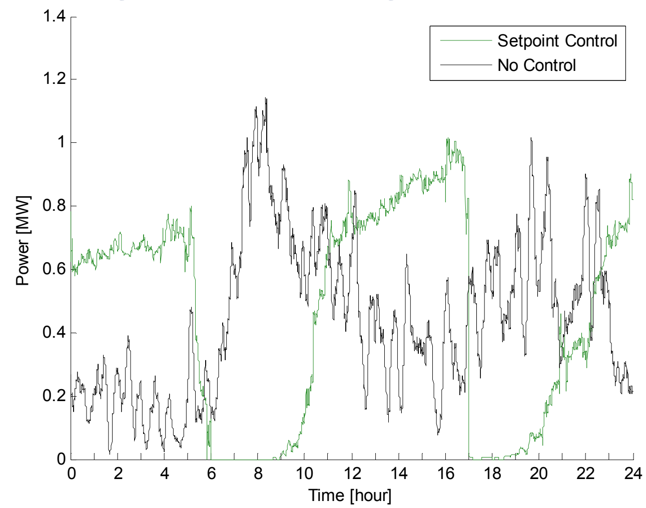




DR for Load Shifting Using Balancing Reserve Signal



Outgoing water temperature of 1000 EWHs



Total power demand of 1000 EWHs in a day

Toward Hydrogen Economy: Fuel Cells and Electrolyzers

- Hydrogen - an energy carrier – can be stored
- Electrolyzers for hydrogen production
- Hydrogen fuel cells for power generation - essentially electric batteries fueled by hydrogen
- Fuel cell-electrolyzer and reversible fuel cells can be used for power generation and hydrogen production

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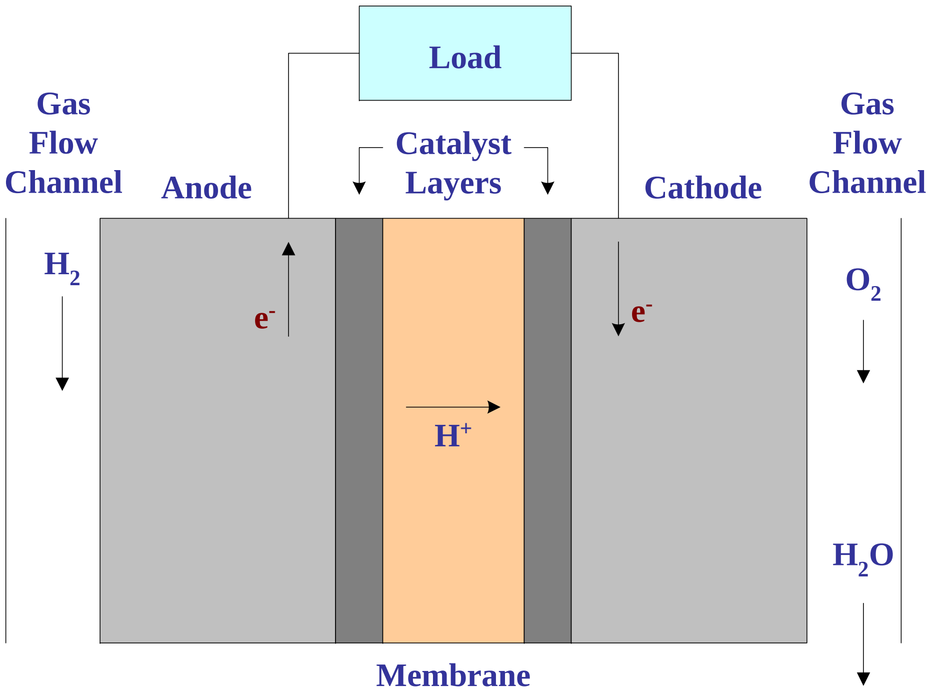
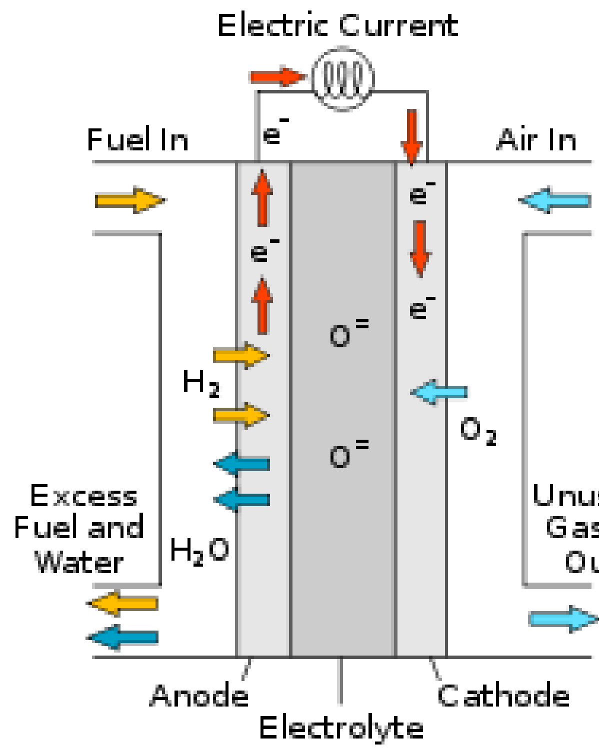
PEM and Solid-Oxide Fuel Cells for Distributed Generation Applications



PEMFC, low temperature: Hydrogen ion transfer through the membrane



SOFC, high temperature: Oxygen ion transfer through the membrane

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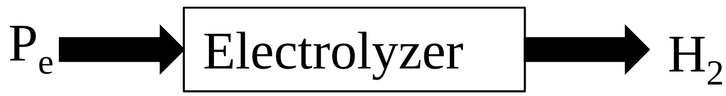
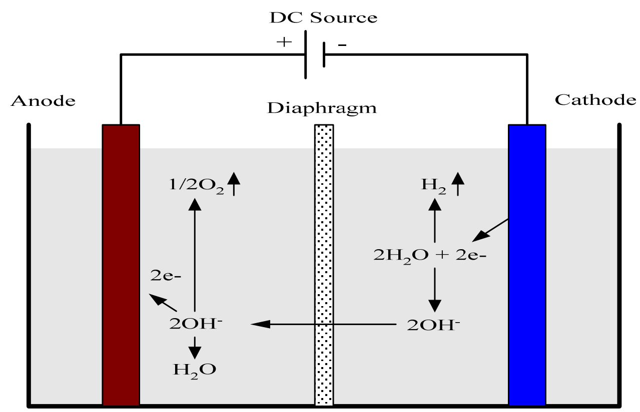
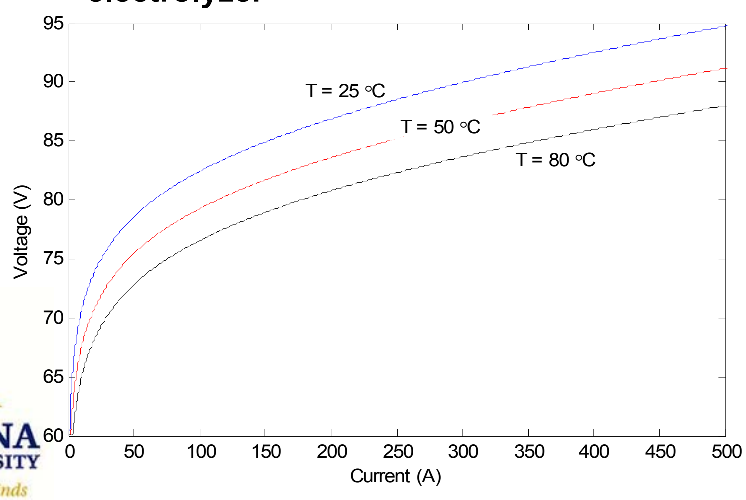
Electrolyzer:
Water Electrolysis and Hydrogen Production





Schematic diagram of an alkaline electrolyzer



$$2H_2O + 2e^- \rightarrow H_2\uparrow + 2OH^-$$

$$2OH^- \rightarrow \frac{1}{2}O_2\uparrow + H_2O + 2e^-$$

$$H_2O \rightarrow H_2\uparrow + \frac{1}{2}O_2\uparrow$$

Glassgow University Chemistry Department reports (August 2014):

Water splitting and hydrogen production 30 times faster than the current method using a molecular metal oxide redox mediator.

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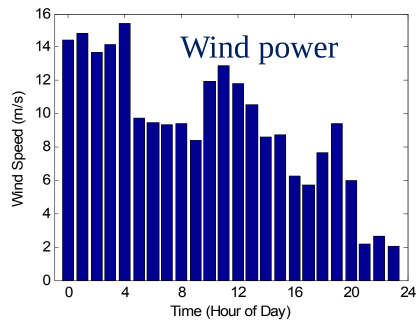
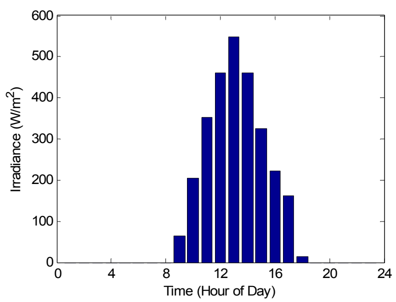
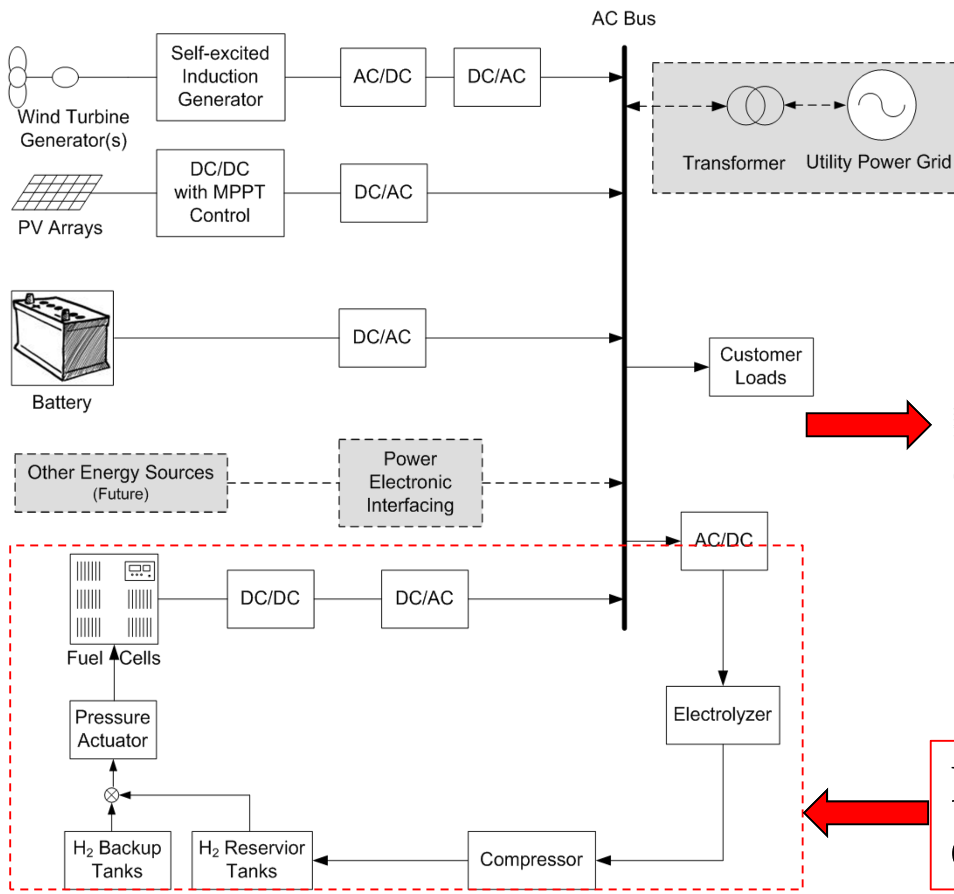
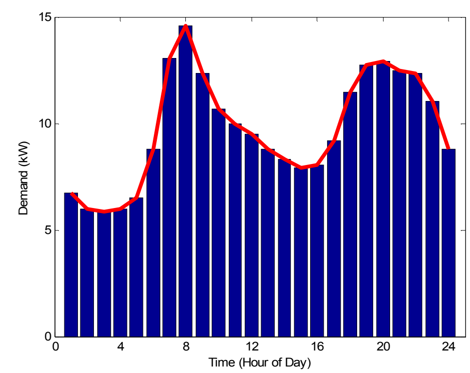
Hybrid wind-PV-FC-Electrolyzer System





Solar power





Load

Fuel-cell-electrolyzer storage

Direct High Temperature Electrolysis

- Electrolysis reaction becomes more efficient at higher temperatures
- Water begins decomposing into hydrogen and oxygen around 2000^{o}C without the need for electric current
- Steam from a concentrated solar thermal plant can be used to produce direct electrolysis at high temperatures

FP6 Hydrosol II is a plant in Spain that uses concentrated thermal energy to produce hydrogen that has been operating since 2008.

http://www.psa.es/webeng/instalaciones/receptor.php

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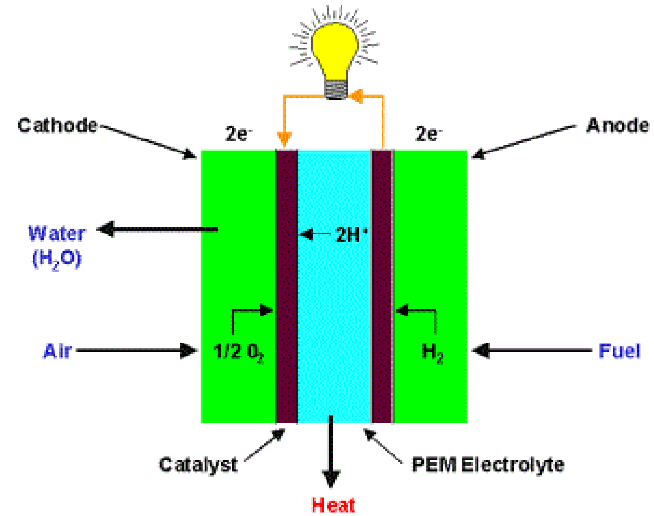
Hydrogen Vehicles

- Hydrogen fuel cell vehicles
  - Several automobile manufacturing companies have fuel cell vehicle programs.



- Hydrogen internal combustion engine (ICE) vehicles

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Hydrogen Safety

- Left: a vehicle with a hydrogen tank.
- Right: a vehicle with a standard gasoline tank.
- Both tanks have been deliberately punctured and ignited.
- Due to the buoyancy of hydrogen, the flame shoots up vertically
- Gasoline is heavy and spreads beneath the vehicle

3 seconds after ignition:

60 seconds after ignition

Source: University of Miami.

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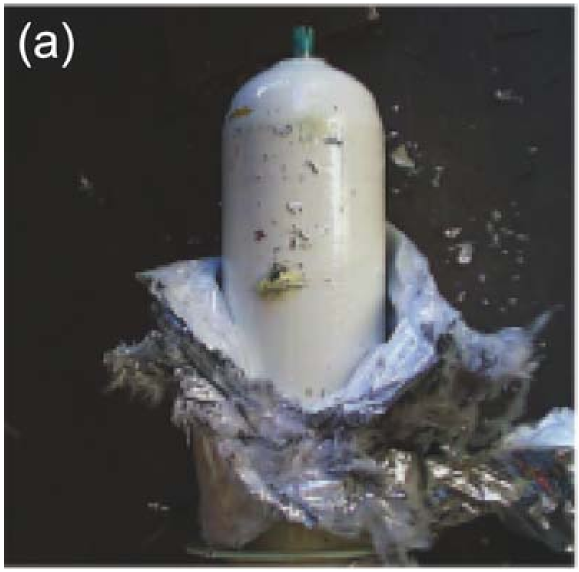
Hydrogen Safety Cont'd

Destructive tests on full hydrogen tanks under extreme conditions



(a) piercing the tank with .30-caliber armor-piercing bullets

(b) bathing the tank in flames for over 60 minutes at 1000 C

No explosion occurred!!

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Source: Lawrence Livermore Laboratories.

For How Long World Energy Needs can be Provided from a Single Fuel?

Long-range green energy source →

Energy source	Utility time
Solar-hydrogen	1-billion years
Nuclear fusion	100 years
Coal	35 years
Gas	14 years
Oil	14 years
Nuclear fission	5 years

Derek Abbott, "Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs?," *Proceedings of the IEEE, Vol. 98, No. 1, 2010*

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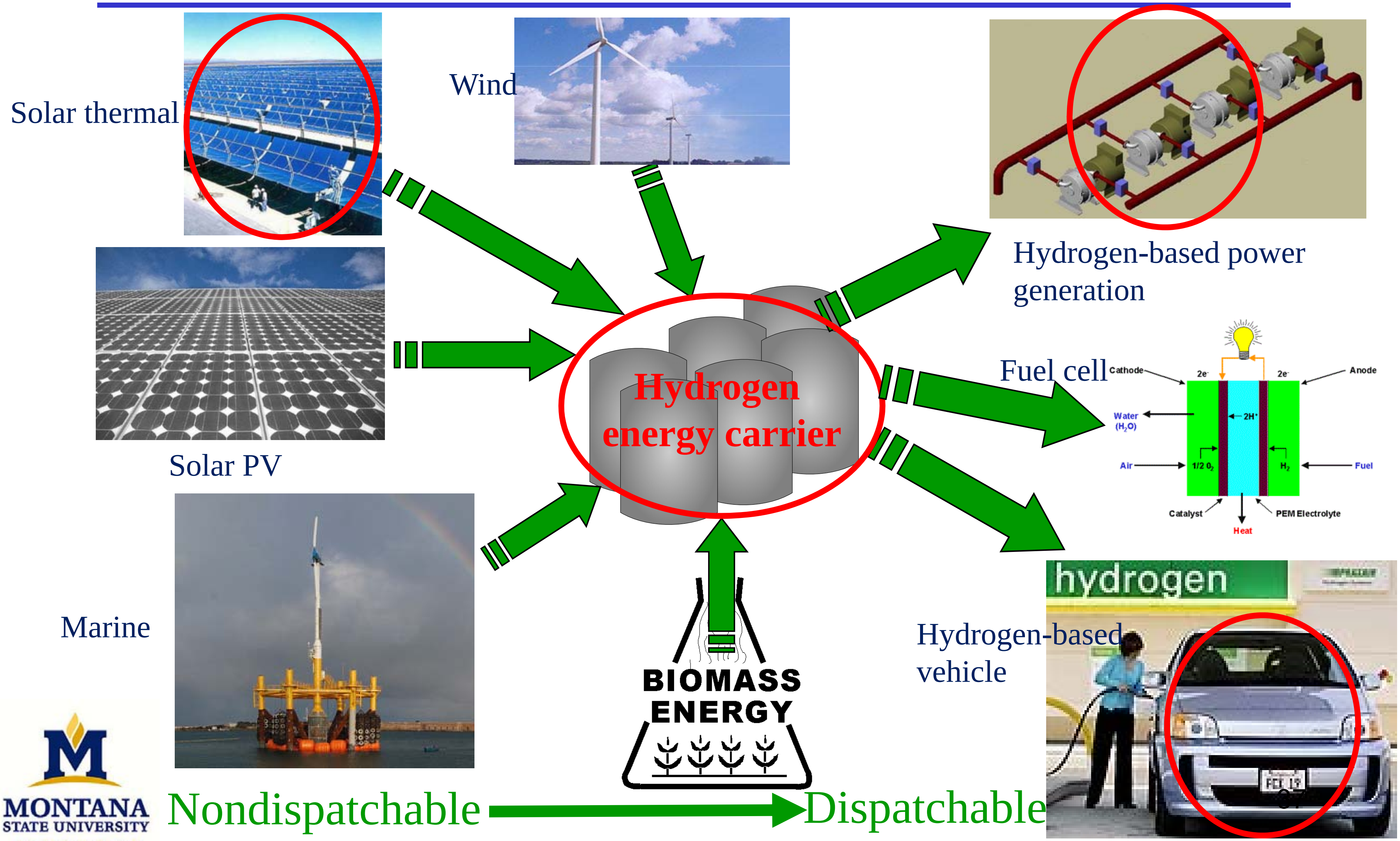
A Vision for Hydrogen Economy Society



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In Conclusion

- Microgrids can make our power systems more reliable – resilient.
- There are many renewable energy resources we can draw on to replace fossil fuels.
- Energy storage devices have an important role in the utilization of intermittent renewable energy – breakthroughs needed!
- Hydrogen energy conversion and storage system could ultimately be the energy option for the future.

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Thank you! (hnehrir@ece.montana.edu)

Enjoy some geological wonders of Montana!

Old Faithful, Yellowstone National Park
Eruption: About every hour, 180 feet, 1 to 5 minutes