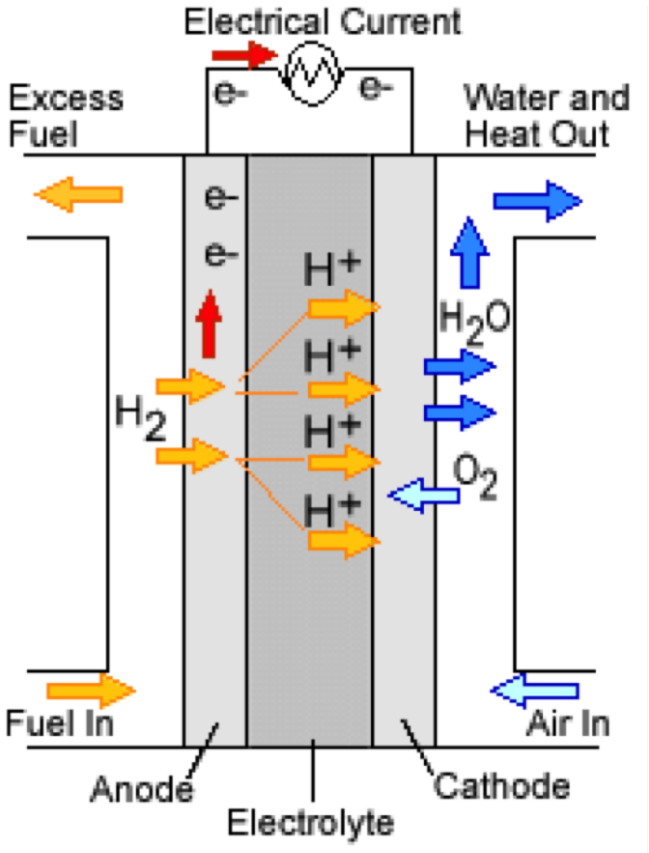
Energy from Electron Transfer

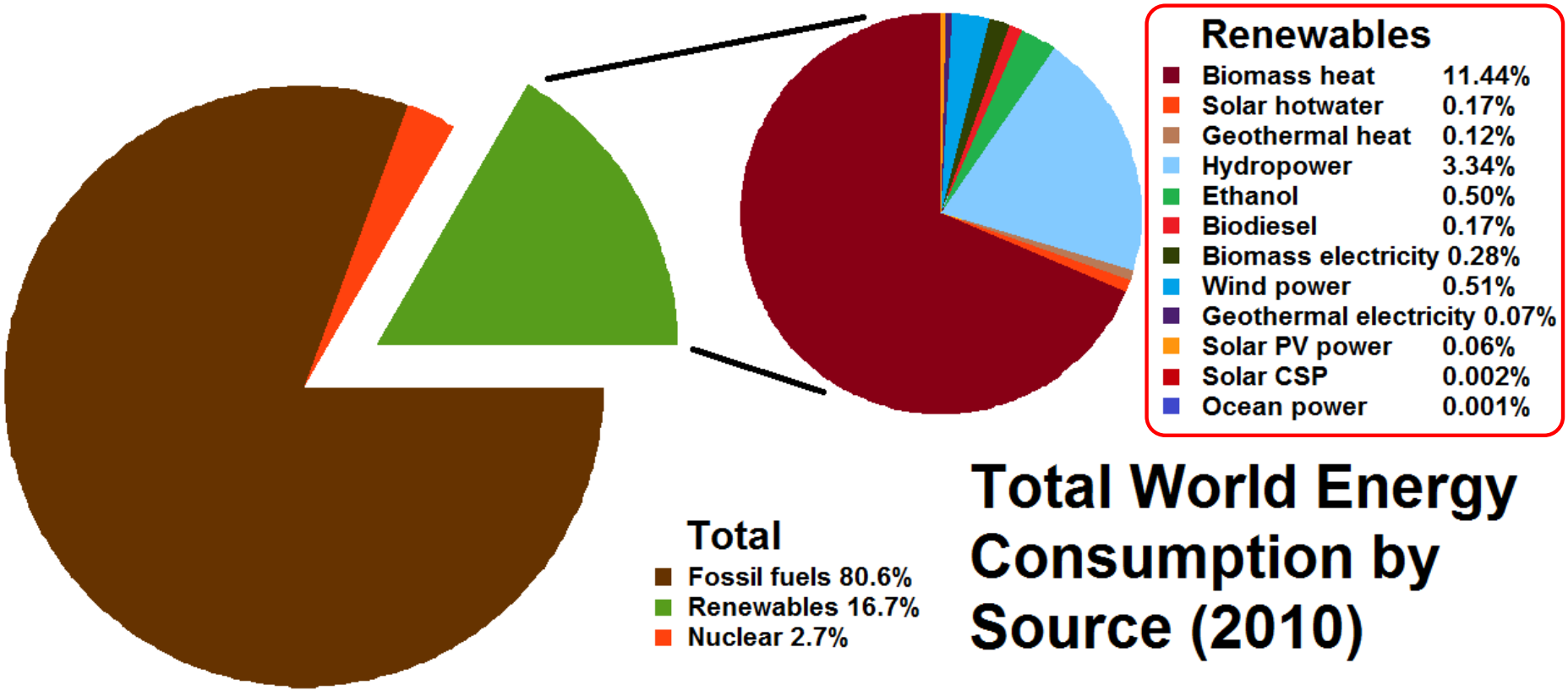
Batteries and Fuel Cells



Outline of Topics

Lecture Question

What are the renewable energy sources? Be as comprehensive as possible. Which of these do you think of as 'clean?'



- About 80% of energy from (nonrenewable) fossil fuels
- Over 90% of energy from combustion

Biomass Energy (Review)

Remind me: what are the environmental impacts of using biomass energy?

Potential advantages:

- Renewable/sustainable energy source
- More versatile than other renewable sources
- Theoretically/ideally only minor impact on global carbon cycle

Potential disadvantages:

- Air quality problems from combustion
- Water quality problems from intensive agriculture
- Increase in food prices
- Generally: envmtl/social impact very dependent on biomass source

Geothermal Energy

How does it work?

- Geothermal power plants: use earths heat to power steam turbines
- Geothermal direct use: use hot springs (etc) as heat source
- Geothermal heat pumps
  - Heating and cooling, uses ground as heat source/sink
  - Temperature of ground below 6 ft is equal to average annual temperature of the surroundings
  - *Not truly geothermal*: energy source is the sun
  - 'Ground-source heat pump' or 'geo-exchange system' are better terms
  - Unlike power plants and direct use, can work in virtually any location
  - According to the EPA: *the most efficient, clean and cost-effective space heating system available*.

Geothermal Energy

What are its advantages and disadvantages as an energy source?

Advantages?

- Renewable
- Easy to exploit in some cases
- Carbon efficiency generally better than fossil fuels
- High net energy yield

Disadvantages?

- Not available everywhere
- Releases some noxious gases, including hydrogen sulfide (H_2S), methane, (CH_4), ammonia (NH_3), carbon dioxide (CO_2)
- Land subsidence, groundwater depletion can be a problem
- Can produce some water pollution

Radiant Solar Energy

How does *radiant solar energy* work as an energy source?

- Solar power plants: steam produced to turn turbine (heat engine)
- Solar heating: active and passive systems
  - Active solar heating requires another energy source to power pumps, fans, (etc) to move the heat
  - Passive solar heating uses no other energy source
- Photovoltaic cells: 'solar cells' use special semiconductors.

Radiant Solar Energy

What are the advantages and disadvantages of solar/PV as an energy source?

Advantages?

- Renewable
- High energy yield
- A very clean source of energy
- No air/water pollution during operation
- Low operating costs; capital costs decreasing
- Will pay for themselves over time

Disadvantages?

- Intermittent source: energy storage issues
- Low energy density: requires pretty much land area
- Materials for PV cells not necessarily renewable

Hydro Energy

How does it work and what are its advantages and disadvantages?

- River is dammed to create a reservoir
- Volume/size of reservoir represents stored hydrologic (potential) energy
- Flowing water turns turbine to generate electricity

Advantages?

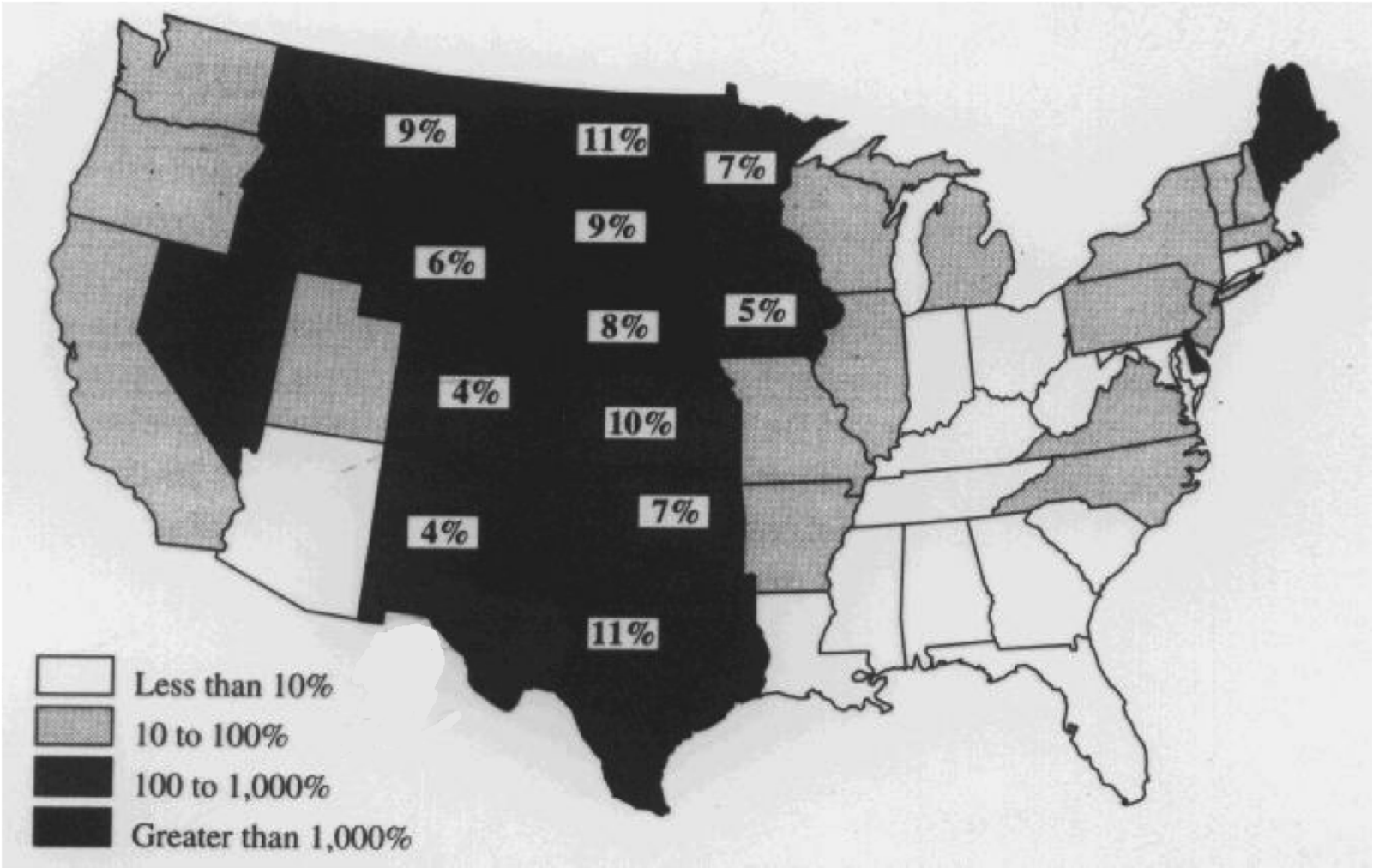
- Cheap to operate
- Renewable
- High yield (not a heat engine)
- Pretty plentiful
- Not intermittent
- Reservoirs have multiple uses
- Less air pollution than combustion heat engines

Disadvantages?

- Human population displacement
- More significant breeding ground for disease
- Reduces availability of water downstream
- Ecosystem impacts
- Water pollution problems
- Air pollution
- Decommissioning is a challenge

Wind Energy

How does it work?



- Shading gives potential for in-state electrical needs
- Numbers give potential for all US electricity

Wind Energy

What are the advantages and disadvantages of wind energy?

Advantages?

- High energy yield (not a heat engine)
- Renewable
- Very clean source of energy: no pollution (air or water) during operation
- Long operating life
- Low operating/maintenance costs
- Can be quickly built; not too expensive
- Cost now almost competitive with hydro and fossil fuels
- Compatible with some multiple uses

Disadvantages?

- Energy storage issues
  - Intermittent
  - Must be connected to electrical grid
- Only practical in areas that are windy enough
- Visual and noise pollution
- Danger to some fliers (birds, bats)
- Low energy density of wind: must use large areas of land

Lecture Question

What is a redox reaction? Give an example, and define the following terms: oxidation, reduction, and half reaction.

- When a strip of Zn is submerged into a solution containing Cu^{2+} ions, the metal becomes tarnished

$$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu(s)$$

- Oxidation half-rxn: $Zn \longrightarrow Zn^{2+} + 2\,e^-$
- Reduction half-rxn: $Cu^{2+} + 2\,e^- \longrightarrow Cu$

More Redox Reactions

What are some important redox reactions and their corresponding half-reactions?

Hydrogen fuel cells are based on the oxidation of elemental hydrogen gas to form water:

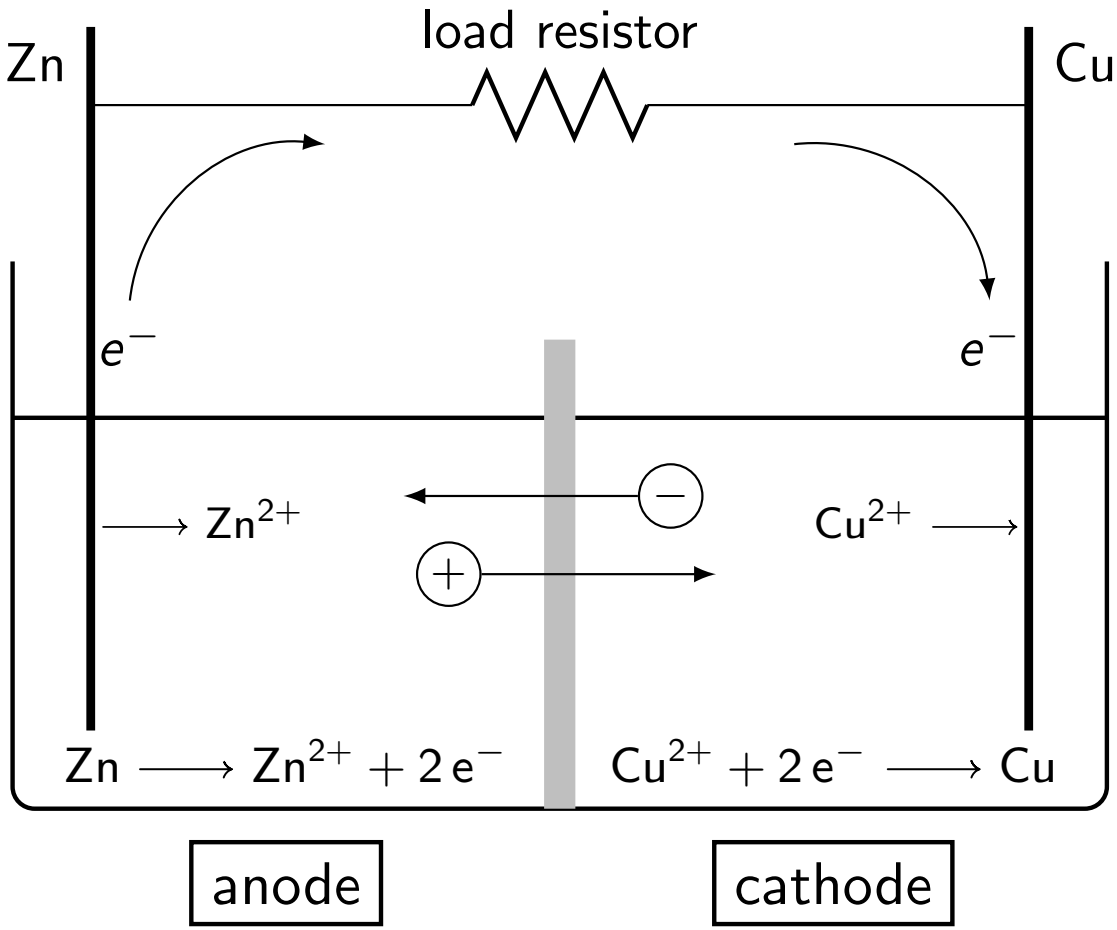
$$2\,H_2(g) + O_2(g) \longrightarrow 2\,H_2O$$

This can be a combustion reaction but it can also happen at the electrodes of a fuel cell.

- Anode (oxidation half-rxn): $2\,H_2 \longrightarrow 4\,H^+ + 4\,e^-$
- Cathode (reduction half-rxn): $O_2 + 4\,H^+ + 4\,e^- \longrightarrow 2\,H_2O$

Lecture Questions

What are batteries and how do they work? Define the *anode* and *cathode*.



Chemical Batteries

What are some key characteristics of chemical batteries? Why are they important?

Characteristics:

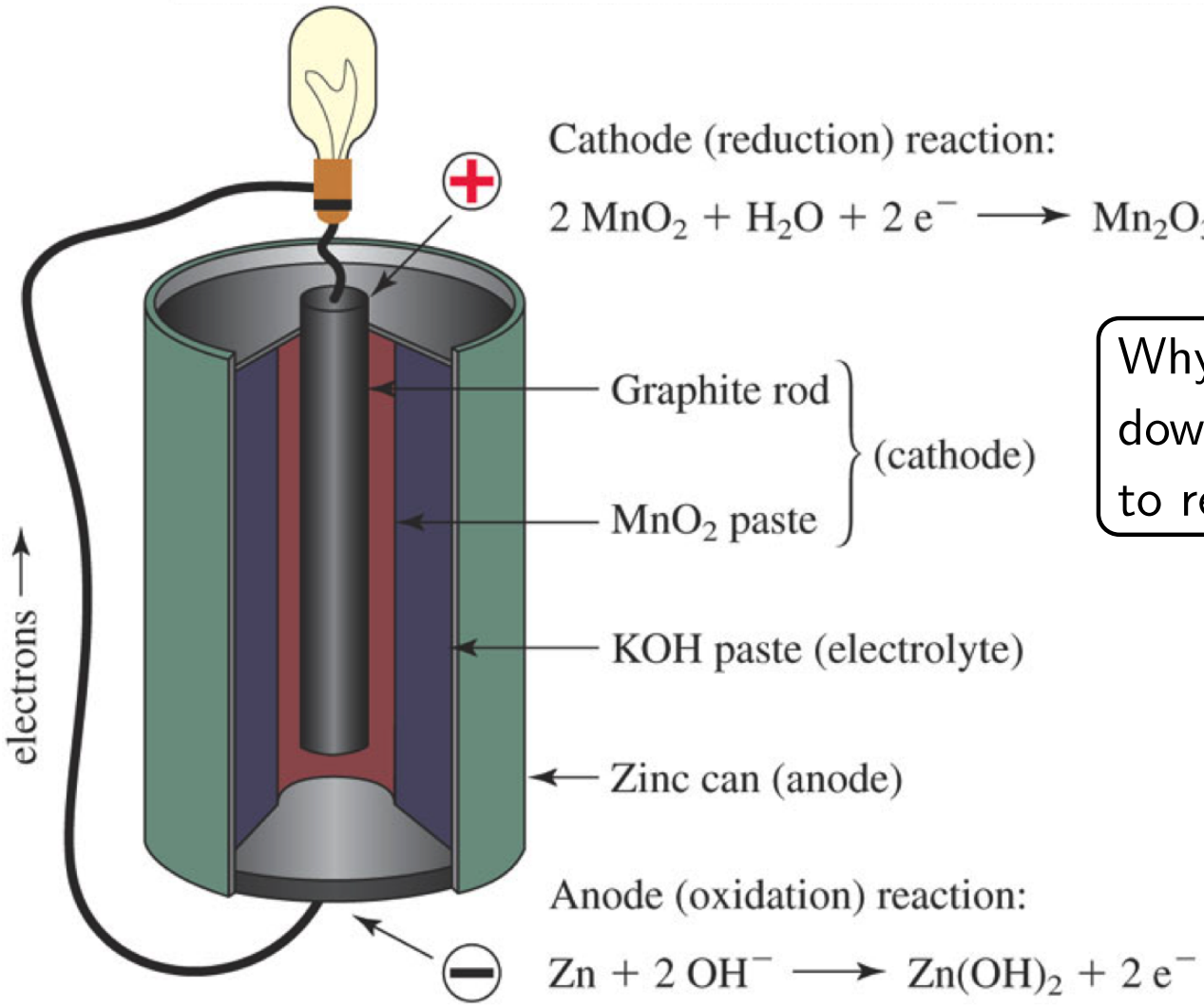
- Redox half-rxns occur at separate electrodes: *reactants never physically meet*
- LEO goes GER
- Electrons generated at anode, flow thru external circuit to cathode
- Anode is oxidation, cathode is reduction
- Redox rxn must be fast enough to generate a useful current at operating conditions

Importance:

- Rechargeable batteries are the most widely used method of electricity storage
- Fuel cells offer a scalable, clean, efficient way to convert chemical energy to electricity

Lecture Question: Alkaline Batteries

How does the alkaline cell work?



Why does a battery run down? What are the options to re-use it?

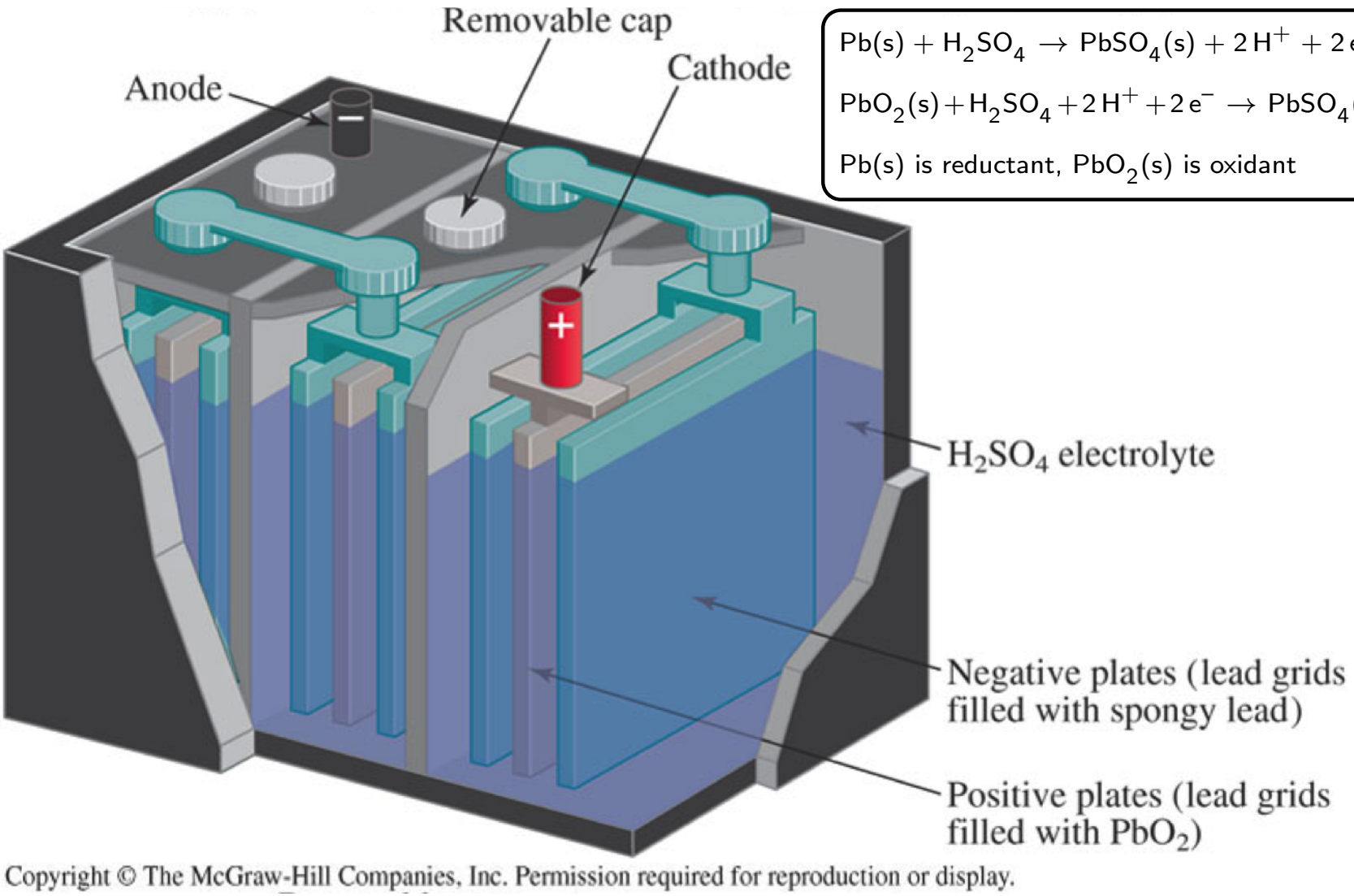
Lecture Question: Rechargeable Batteries

How do rechargeable batteries work?

- Galvanic *vs* electrolytic cells. Illustrate the latter with water.
- Rechargeable cells: electrolytically re-generate the reactants.
- Not all redox rxns are reversible
- Side rxns limit the number of recycles
- Many modern electronics use rechargeables

Lecture Question: Lead Acid Battery

How does the lead-acid storage battery work?



$Pb(s) + H_2SO_4 \rightarrow PbSO_4(s) + 2\,H^+ + 2\,e^-$

$PbO_2(s) + H_2SO_4 + 2\,H^+ + 2\,e^- \rightarrow PbSO_4(s) + 2\,H_2O$

Pb(s) is reductant, $PbO_2(s)$ is oxidant

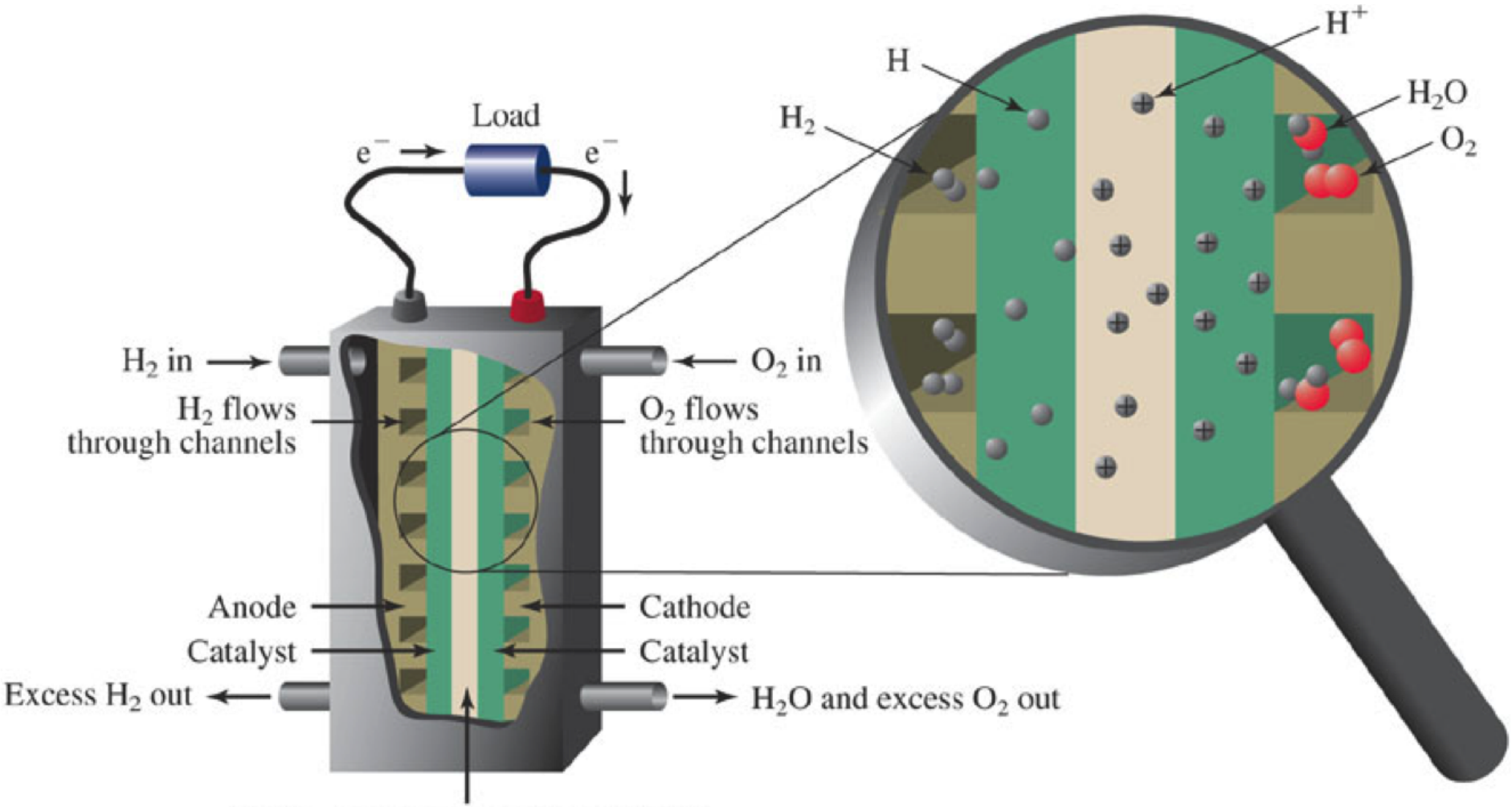
Lecture Questions: Hydrogen Fuel Cells

How do fuel cells work? And what is *distributed generation*?

- A fuel cell is a battery in which the *reactants are continually supplied to the electrodes*, and the products are continually removed.
  - Much more efficient (2-3 times) than heat engines at generating electricity
  - Most common type of fuel cells based on hydrogen (there are others)
- Fuel cells are scaleable
  - Large ones can power homes or neighborhoods
  - Small ones can be used in appliances
- Distributed generation with fuel cells
  - A decentralized power system consisting of hydrogen generators and fuel cells

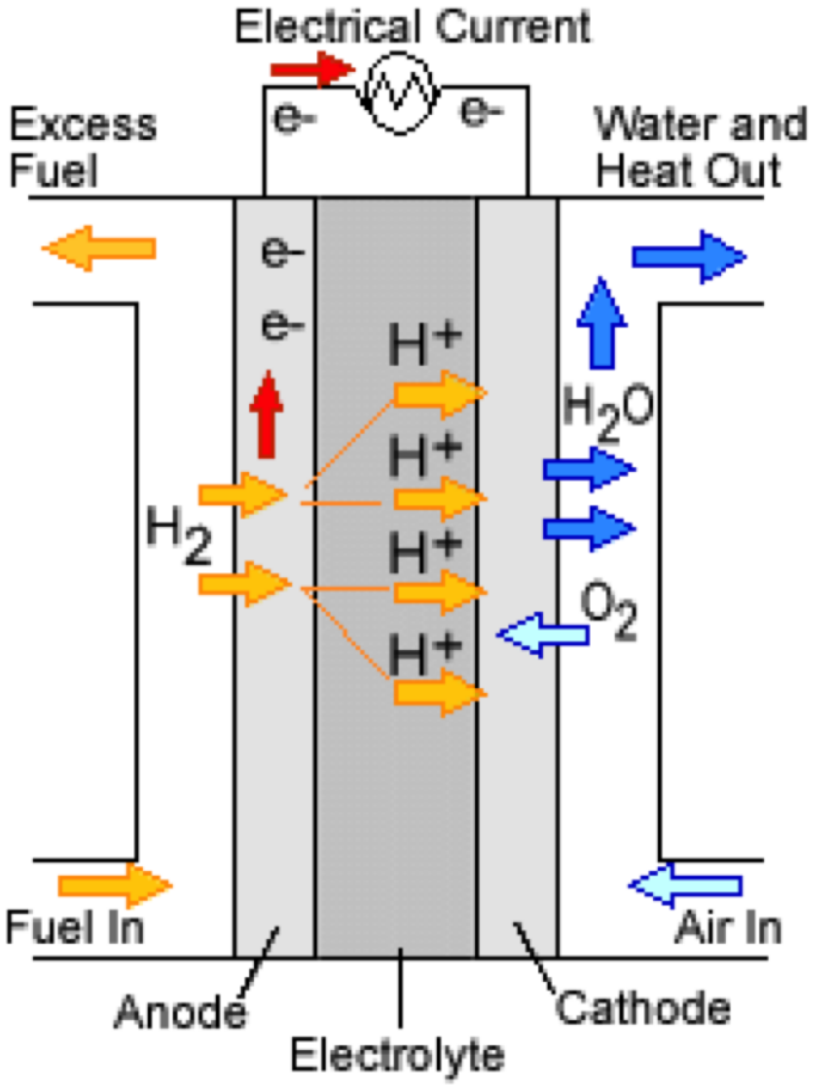
Hydrogen Fuel Cells

What might a H_2 fuel cell look like?



Hydrogen Fuel Cells

What is a *proton exchange membrane* (PEM) fuel cell?



- An ion-conductive barrier ('electrolyte') is needed to prevent bulk mixing but allow current to flow
- Fuel cells are differentiated by fuel and electrolyte barrier
- Also have different power output capabilities and operating temperatures

Hydrogen Fuel Cells

Any other notable fuel cells?

Fuel cell name	Electrolyte	Qualified power (W)	Working temperature (°C)	Efficiency (cell)	Efficiency (system)	Status	Cost (USD/W)
Metal hydride fuel cell	Aqueous alkaline solution		> -20 (50% P_{peak} @ 0 °C)			Commercial / Research	
Electro-galvanic fuel cell	Aqueous alkaline solution		< 40			Commercial / Research	
Direct formic acid fuel cell (DFAFC)	Polymer membrane (ionomer)	< 50 W	< 40			Commercial / Research	
Zinc-air battery	Aqueous alkaline solution		< 40			Mass production	
Microbial fuel cell	Polymer membrane or humic acid		< 40			Research	
Upflow microbial fuel cell (UMFC)			< 40			Research	
Regenerative fuel cell	Polymer membrane (ionomer)		< 50			Commercial / Research	
Direct borohydride fuel cell	Aqueous alkaline solution		70			Commercial	
Alkaline fuel cell	Aqueous alkaline solution	10 – 100 kW	< 80	60–70%	62%	Commercial / Research	
Direct methanol fuel cell	Polymer membrane (ionomer)	100 mW – 1 kW	90–120	20–30%	10–25%[47]	Commercial / Research	125
Reformed methanol fuel cell	Polymer membrane (ionomer)	5 W – 100 kW	250–300 (Reformer) 125–200 (PBI)	50–60%	25–40%	Commercial / Research	
Direct-ethanol fuel cell	Polymer membrane (ionomer)	< 140 mW/cm²	> 25 ? 90–120			Research	
Proton exchange membrane fuel cell	Polymer membrane (ionomer)	1 W – 500 kW	50–100 (Nafion)[48] 125–220 (PBI)	50–70%	30–50%[47]	Commercial / Research	50–100
RFC – Redox	Liquid electrolytes with redox shuttle and polymer membrane (Ionomer)	1 kW – 10 MW				Research	
Phosphoric acid fuel cell	Molten phosphoric acid (H_3PO_4)	< 10 MW	150-200	55%	40%[47] Co-Gen: 90%	Commercial / Research	4–4.50
Solid acid fuel cell	H^+-conducting oxyanion salt (solid acid)	10 W - 1 kW	200-300	55-60%	40-45%	Commercial / Research	
Molten carbonate fuel cell	Molten alkaline carbonate	100 MW	600–650	55%	45-55%[47]	Commercial / Research	
Tubular solid oxide fuel cell (TSOFC)	O^{2-}-conducting ceramic oxide	< 100 MW	850–1100	60–65%	55–60%	Commercial / Research	
Protonic ceramic fuel cell	H^+-conducting ceramic oxide		700			Research	
Direct carbon fuel cell	Several different		700–850	80%	70%	Commercial / Research	
Planar Solid oxide fuel cell	O^{2-}-conducting ceramic oxide	< 100 MW	500–1100	60–65%	55–60%[47]	Commercial / Research	
Enzymatic Biofuel Cells	Any that will not denature the enzyme		< 40			Research	
Magnesium-Air Fuel Cell	Salt water		–20 to 55	90%		Commercial / Research	

(Click above for link)

Lecture Question/Class Exercise

Make a list of the environmental impacts of batteries, including fuel cells.

- Use of the battery is clean but that doesn't mean no impact
- Cradle-to-grave analysis needed, including obtaining raw materials (eg through mining), battery manufacture, and disposal
- Many use toxic or precious metals
- Materials used in battery are not necessarily renewable or obtained in a sustainable manner

The Hydrocarbon (Fossil Fuel) Economy

Describe, in a broad sense, how the current hydrocarbon economy works to deliver energy to the end user.

Largely dependent on *combustion-based heat engines*. For example:

- Transportation: oil is extracted, refined, and burned at the source in an internal combustion engine.
- Electricity generation: fossil fuels burned in a steam turbine.
- On-site combustion of fuel for heat.

So we distribute most of our energy as a hydrocarbon fuel that is burned, or as electricity generated from burning a hydrocarbon.

Lecture Question: The Hydrogen Economy

What is the hydrogen economy?

- The Hydrogen Economy is a hypothetical large-scale system in which elemental hydrogen (H_2) is the primary form of energy storage
- Fuel cells would be the primary method of conversion of hydrogen to electrical energy
- Efficient and clean; scalable
- Hydrogen (usually) plays a central role in transportation

Potential Advantages

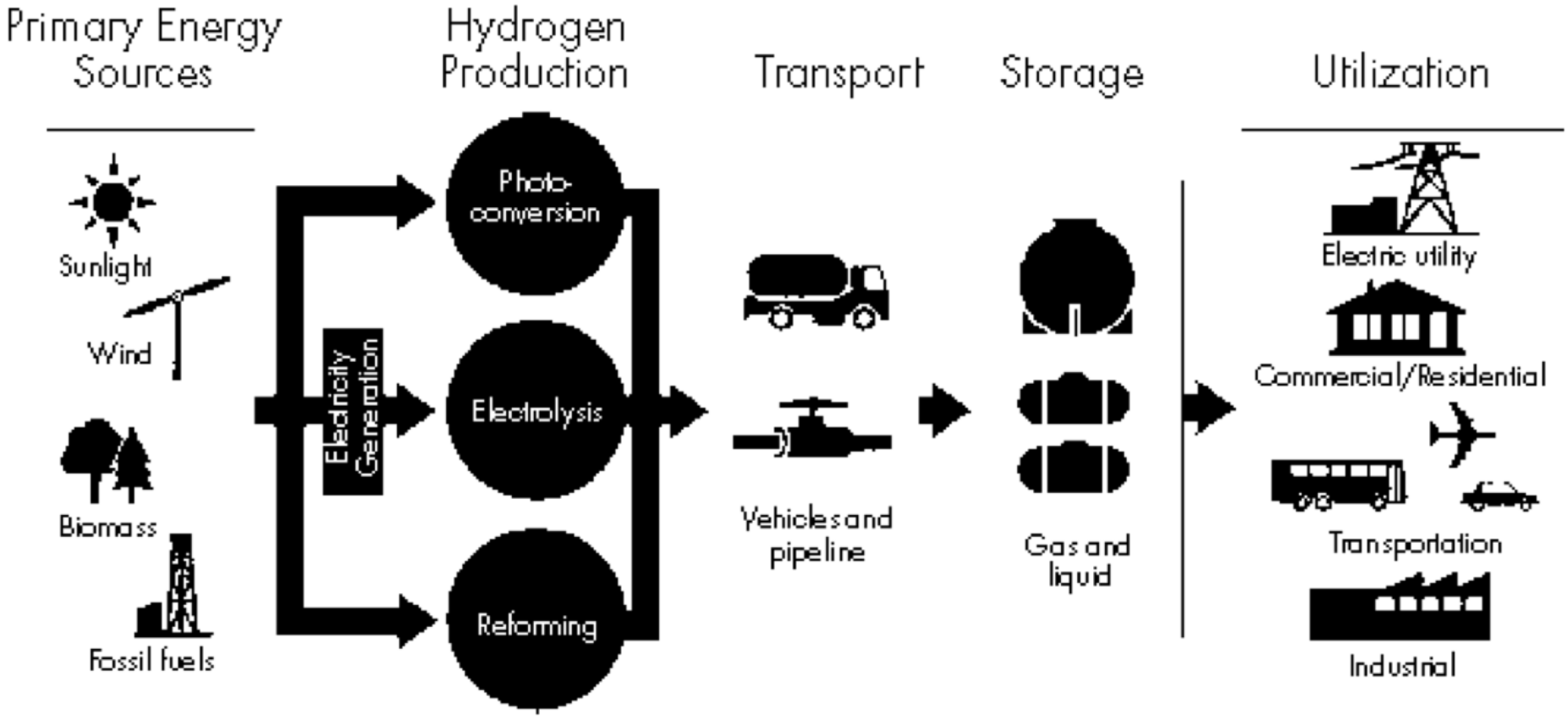
- Clean, renewable
- Potentially more reliable (using distributed generation)

BUT many roadblocks including potential show-stoppers

- Poses great technological challenges for efficient hydrogen production, storage, and transport

Lecture Question: The Hydrogen Economy

What are the components of the hydrogen economy?



Components: production, storage, delivery, end use.

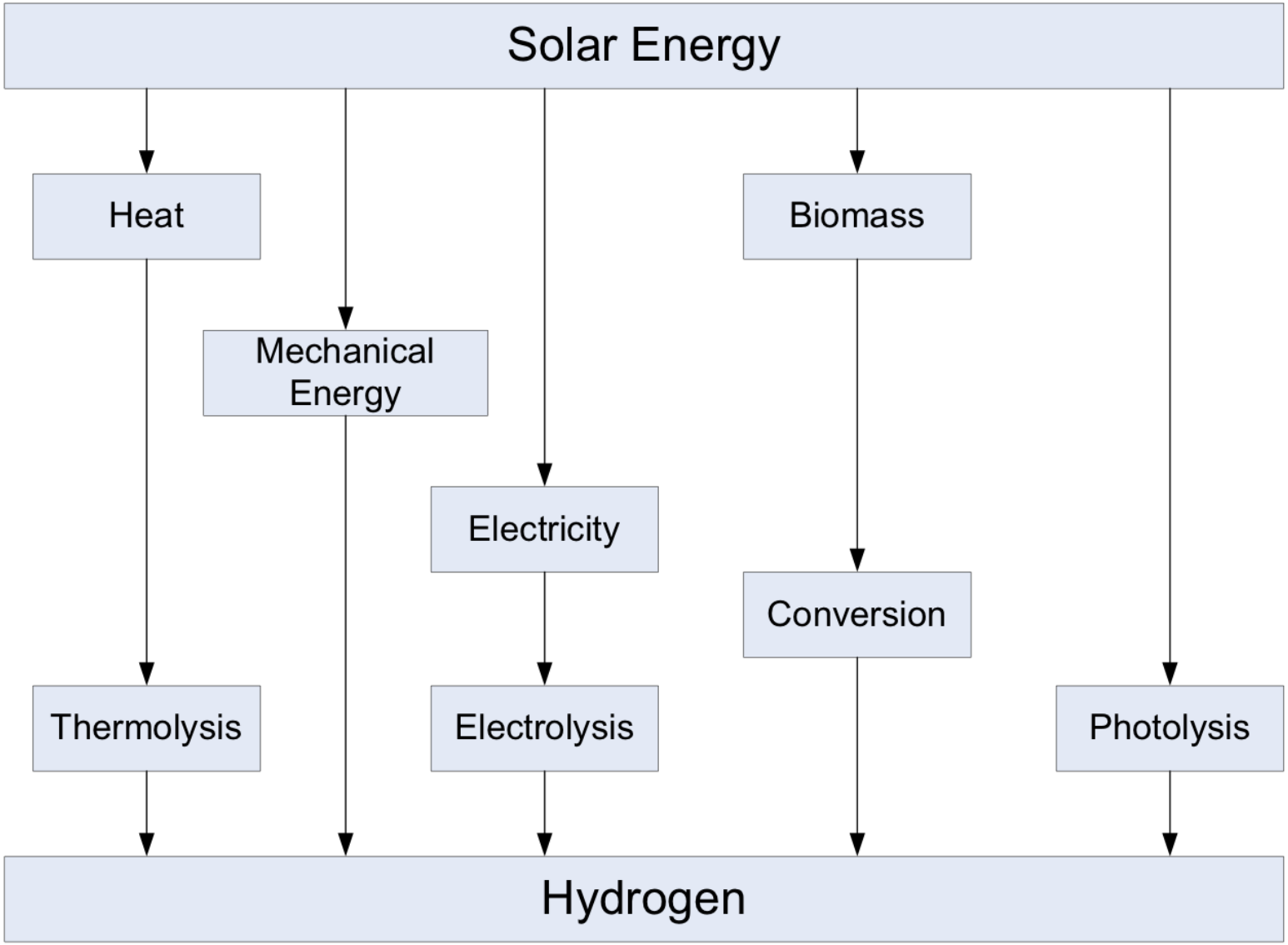
The Hydrogen Economy

How is hydrogen gas produced?

- Fossil Fuels
  - Steam reforming of natural gas
  - Partial Oxidation (POX) of Hydrocarbons
  - Coal Gasification
- Electrolysis of water
  - Efficiencies 70–85%
  - Produces highest purity of hydrogen
  - Currently, the electricity consumed is usually worth more than the hydrogen produced
- Experimental methods
  - Biological hydrogen production
  - Direct photolysis
  - Thermolysis

The Hydrogen Economy

Summarize the renewable paths to H_2 production.



The Hydrogen Economy

Is a hydrogen economy in our future? Are there alternatives?

- The hydrogen economy has its share of critics
- Alternative: EVs running on 'clean' electricity, and/or plug-in hybrids running on biomass-derived fuels (and clean electricity)
- Some advocate a *methanol economy*