Futures for Hydrogen Produced Using Nuclear Energy

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1st International Conference on Innovative Nuclear Energy Systems for Sustainable Development of the World (COE INES-1)
Tokyo Institute of Technology; Tokyo, Japan
October 31–November 4, 2004

Outline

- **Hydrogen and electricity have different characteristics as energy carriers**
- **Nuclear hydrogen may be the enabling technology for a nuclear-hydrogen renewables energy future**
- **Nuclear hydrogen may fuel future transportation systems**

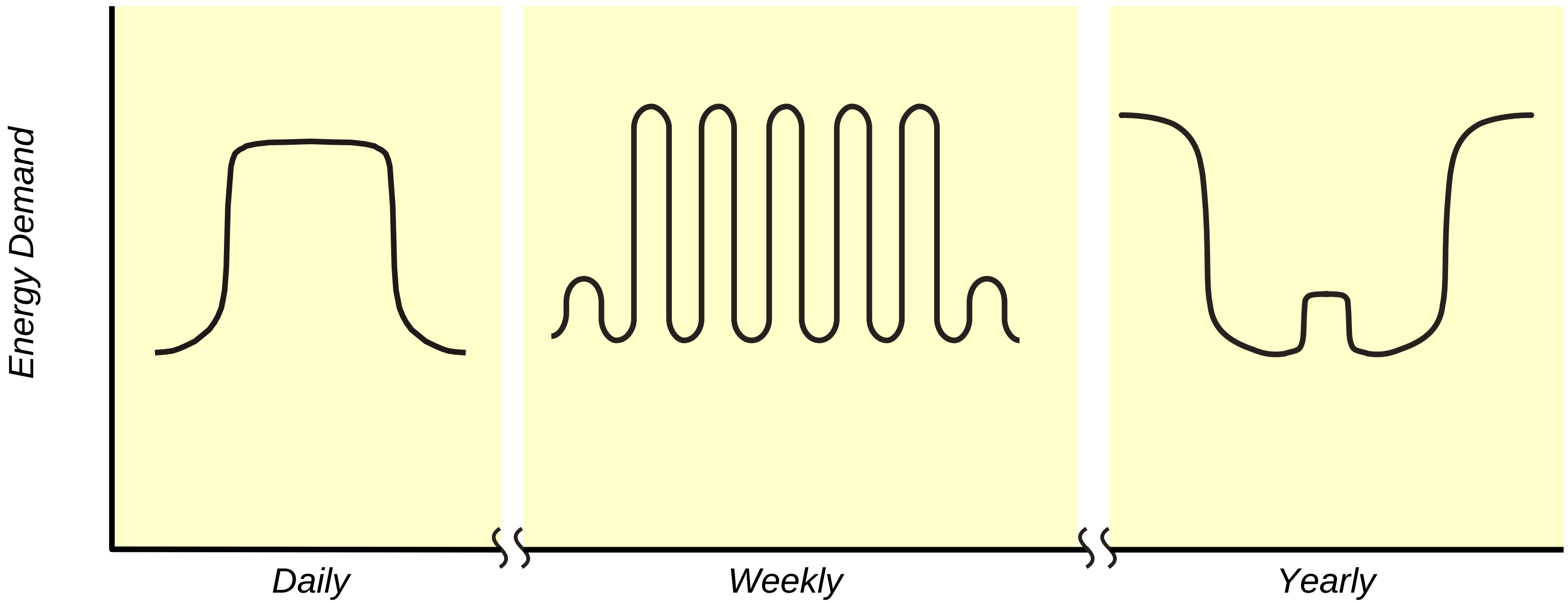
Hydrogen and Electricity have Different Characteristics as Energy Carriers

Storage

Distribution

Production

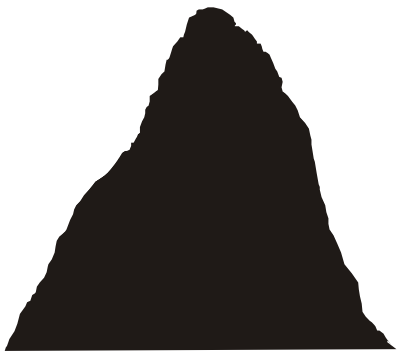
Energy Demand Varies with Time-of-Day, Weekly, and Yearly



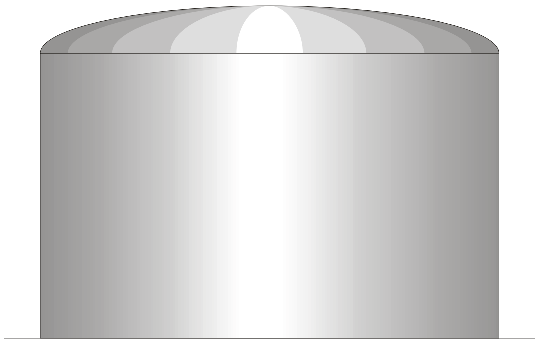
Stored Fossil Fuels are Used to Meet Variable Energy Demands

(Relatively Low Capital-Cost Equipment Converts Fossil Fuels to Electricity)

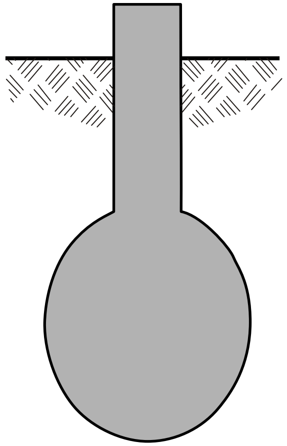
Coal Piles



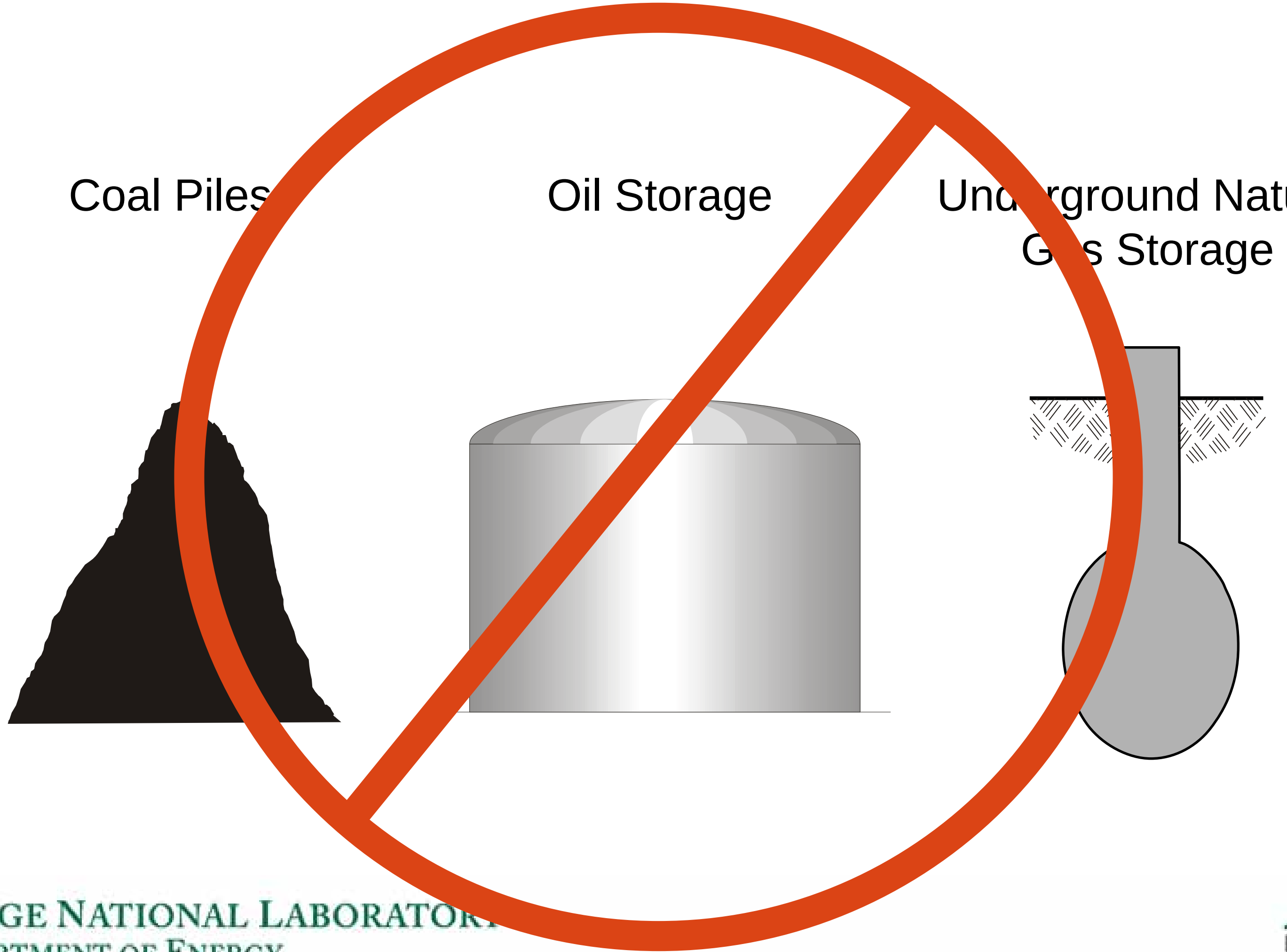
Oil Storage



Underground Natural Gas Storage

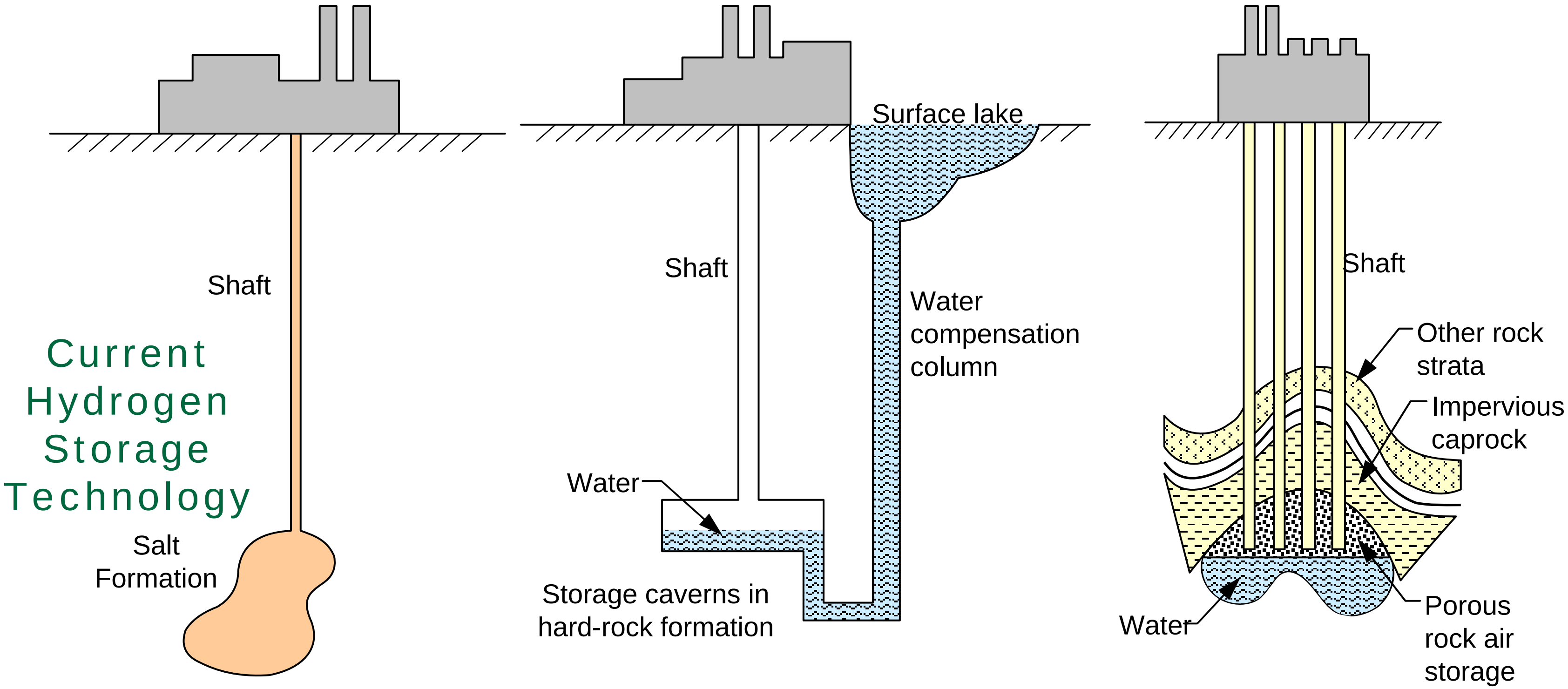


If Fossil-Fuel Usage is Restricted, New Energy Storage Methods are Needed



In the Future, Hydrogen Can be the Technology for Energy Storage

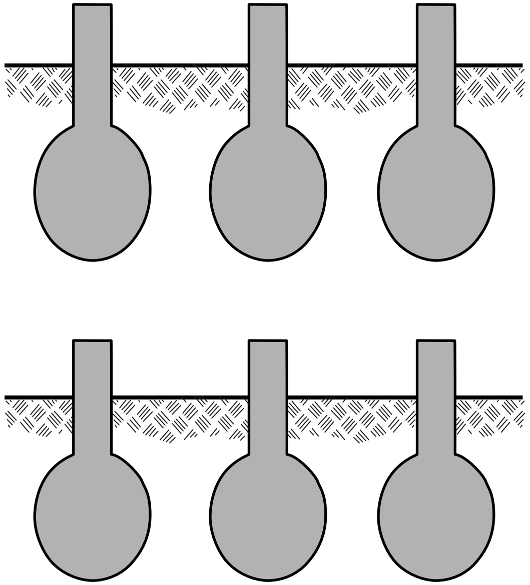
(Same Storage Technology as Natural Gas)



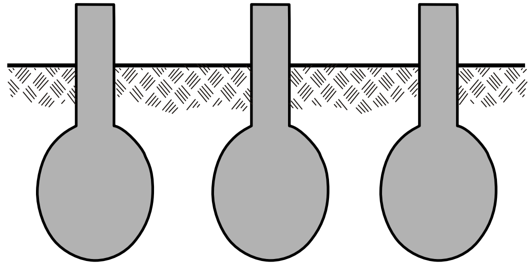
Stored Natural Gas In the U.S. Equals 1/3 of Annual Consumption

Hydrogen Storage Requirements Depend Upon the Match Between Seasonal Energy Demand and Energy Production

Solar Seasonal H_2 Production Not Match Energy Demand



Nuclear H_2 Production More Closely Matches Demand



Nuclear Hydrogen Minimizes Hydrogen Large-Scale Energy Storage Requirements

Hydrogen Collection and Distribution is Different Than Electricity

- **Electricity transport**
  - **Two-way systems with transformers**
- **Hydrogen transport: similar to natural gas**
  - **Hydrogen transmits one way: high-to-low pressure**
  - **Large economics of scale associated with hydrogen compression**
  - **Favors central hydrogen production if connected to large-scale hydrogen storage**

Hydrogen and Electricity have Different Generation Characteristics

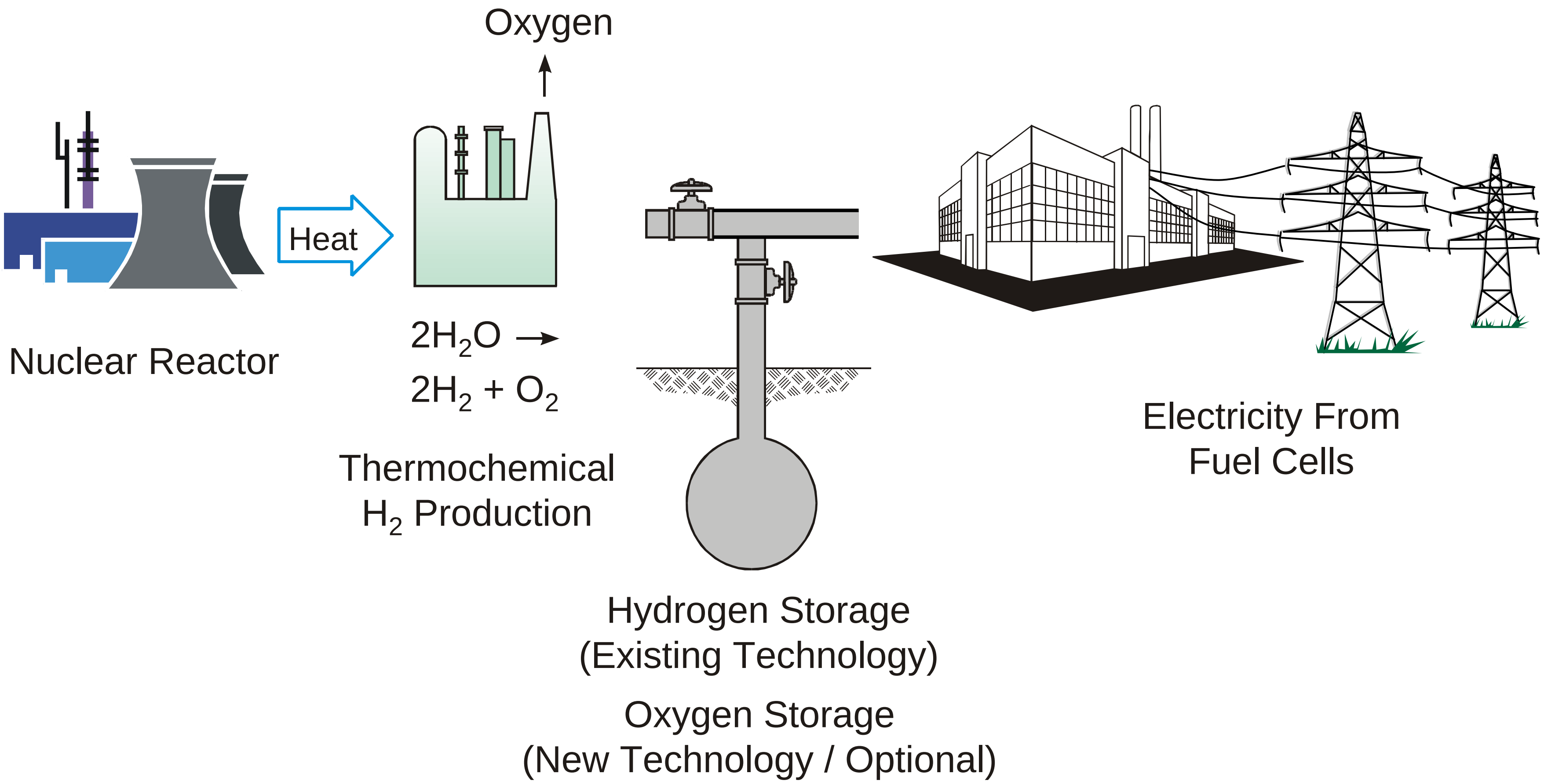
- **Electricity can be economically generated on a large or small scale**
  - **Many generation options**
  - **Moving electrons**
- **Hydrogen is most efficiently generated on a large scale**
  - **Chemical industry experience with economics of scale**
  - **Moving mass**
  - **Favors hydrogen from nuclear energy**

Nuclear-Hydrogen May be the Enabling Technology for a Nuclear-Hydrogen Renewables Energy Future

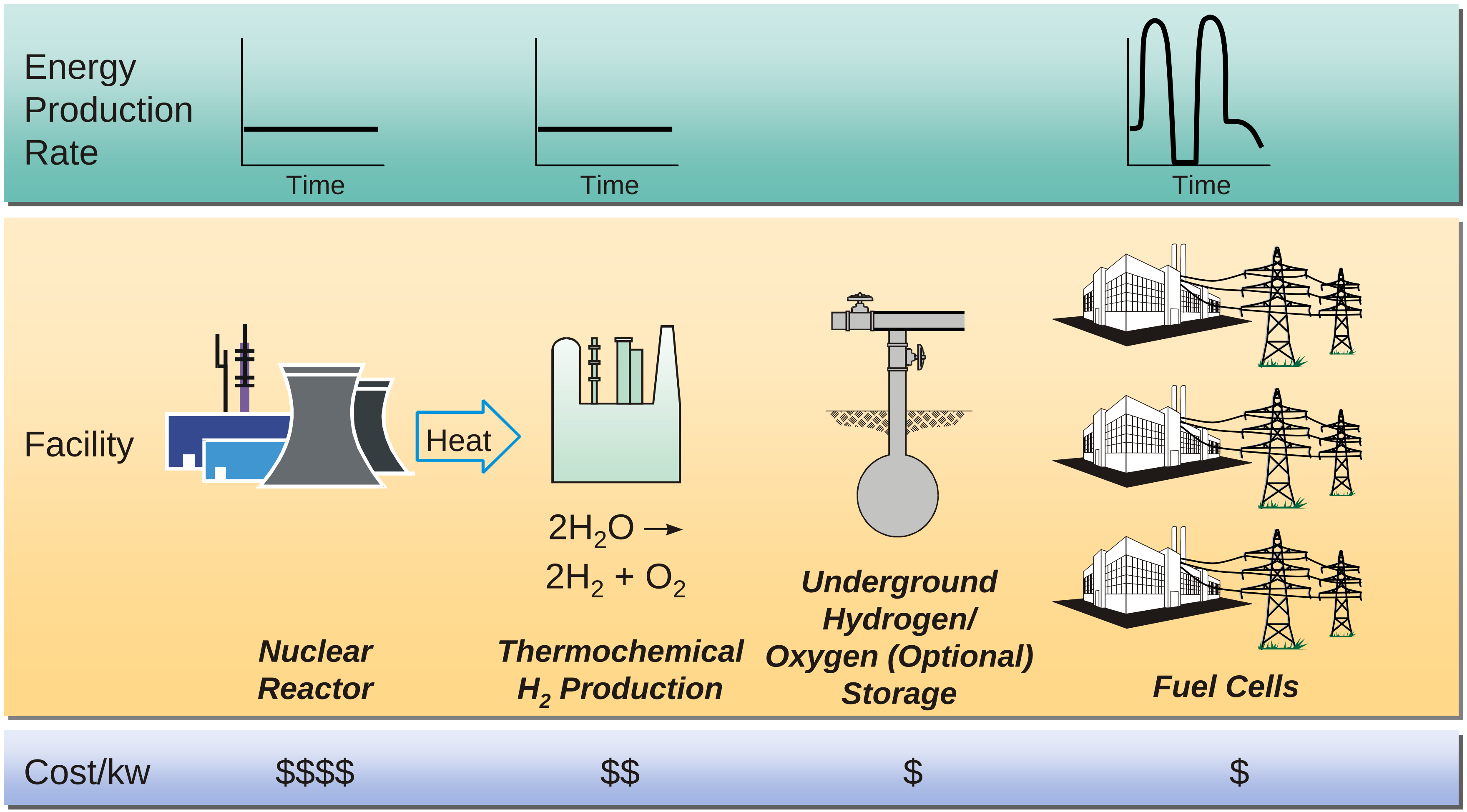
Hydrogen From Nuclear Energy Can Fill the Gap Between Electricity Demand and Electricity Generation by Capital Intensive Nuclear and Renewable Energy Sources

Nuclear Hydrogen May Eliminate the Biggest Barrier to Renewables: Energy Storage

Nuclear Hydrogen May Meet Peak and Intermediate Electric Power Demands and Provide Spinning Reserve



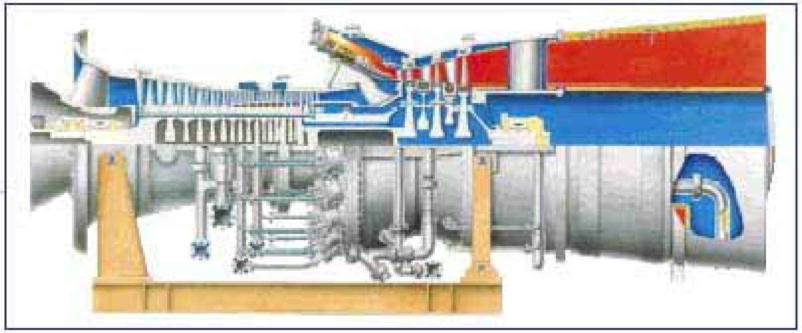
Peak Electric Nuclear System (PENS)



Economic Basis for Peak Electric Nuclear System

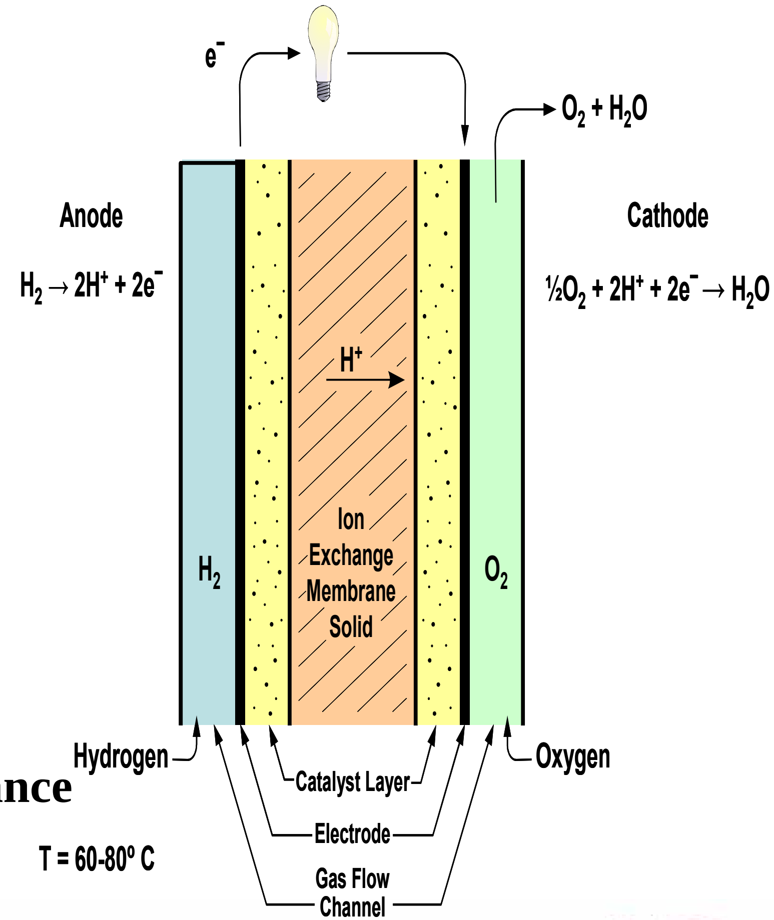
- **Economics-of-scale [1000 MW(e) or more of peak power]**
  - **Hydrogen production**
  - **Low-cost underground hydrogen and oxygen storage**
  - **Large scale fuel-cell complex**
- **Electrical production costs from fuel cells are expected to be less than from gas turbines (the competition)**
  - **Peak electrical power generation requires low capital cost per kW(e) because the power plant operates only a fraction of the year at times of peak electrical demand**
  - **Fuel-cell economic goals are for capital costs <20% of gas turbines; but, fuel cells require hydrogen (premium fuel)**
  - **Fuel cell projected efficiency (80%) is greater than that for gas turbines (50%)**
- **Fuel cells using oxygen have significantly lower costs than fuel cells operated on air**
  - **Improved fuel cell efficiency**
  - **Reduced fuel-cell capital costs by a factor of 3**

Unlike Gas Turbines, Fuel Cell Cost is Reduced and Performance is Improved by Use of Oxygen Rather Than Air



↑ **Brayton Power Cycles**
  Materials limit peak temperature
  Oxygen not a benefit (Heat engine)

Fuel Cells →
  Mass transfer limits performance
  Oxygen (rather than air) boosts performance



PENS Creates the Possibility of a Nuclear-Hydrogen Renewable Economy

- **Renewables (solar and wind) are potentially low-cost energy sources**
- **Cost of energy storage makes large-scale renewable energy systems very expensive**
- **PENS provides variable electricity production, provides energy storage**

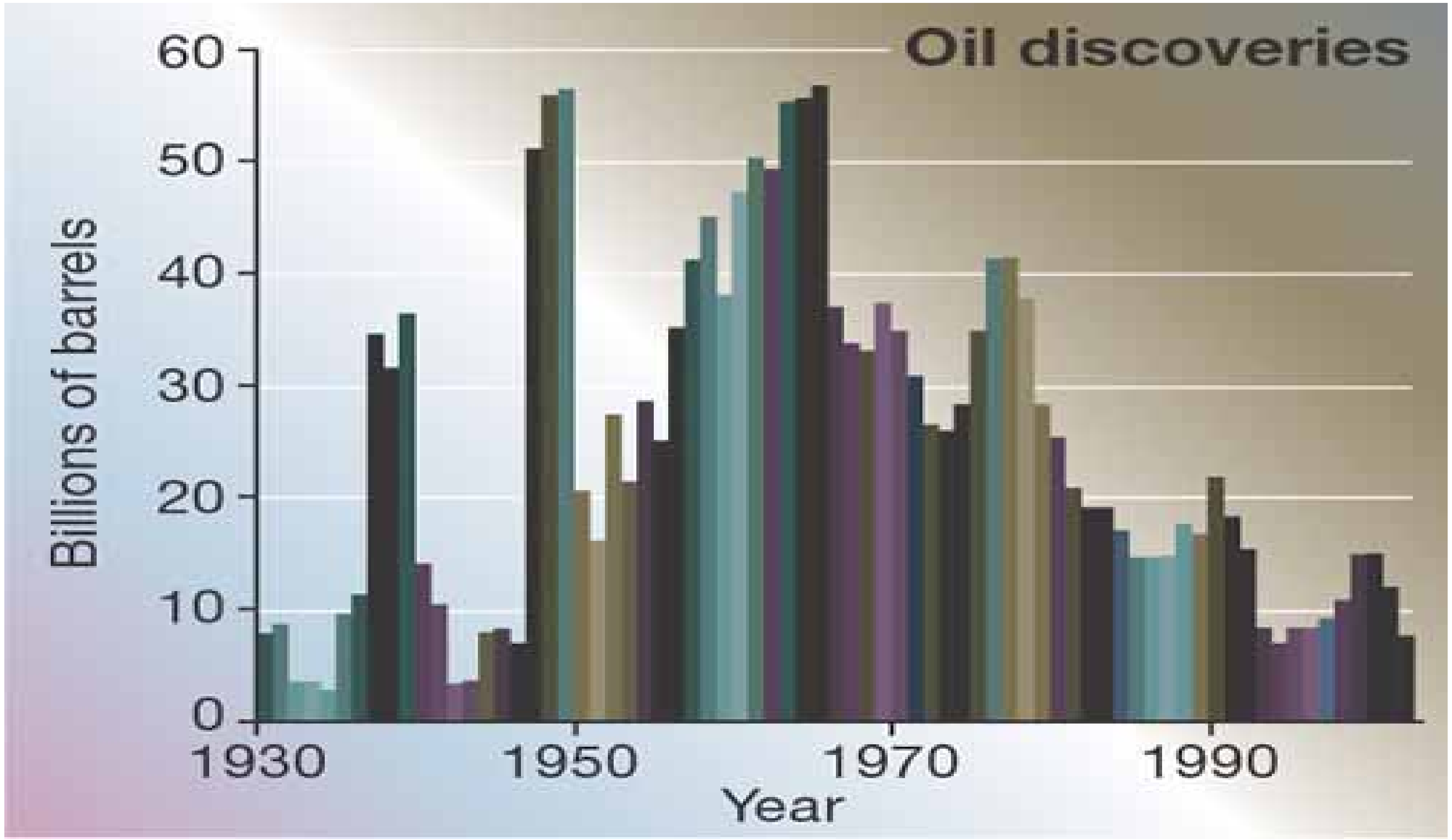
Nuclear Hydrogen May Fuel Future Transportation Systems

Fuels: All Options Require Hydrogen

Engines: A Revolution is Coming

The World is Running Out of Conventional Oil Resources

(Source: Nature: 17 June 2004, p. 694)



The Near-Term Conventional-Oil Replacement will be Liquid Fuels from Heavy Oils and Tar Sands

Syncrude Canada Ltd.
Tar Sands Operations

- **Resources of tar sands and heavy oils far exceed conventional oil resources**
- **Tar sands and heavy oils are converted to liquid fuels by adding hydrogen**
- **Hydrogen production is the key to future liquid fuels production**

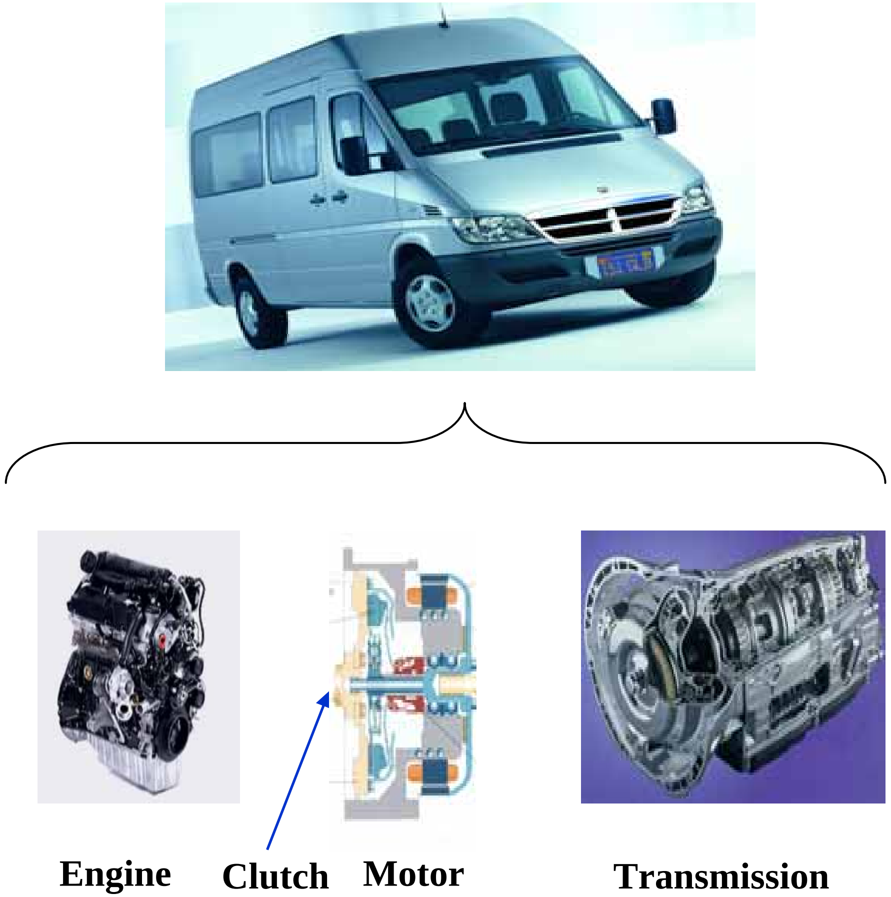
Future Transportation Fuels Favor Large-Scale Hydrogen Production

- **Long-Term Transport Fuels Require Hydrogen**
  - **Heavy Oil + H_2 → Gasoline**
  - **Tar Sands + H_2 → Gasoline**
  - **Solar + Fertilizer (H_2 for ammonia) → Biomass → Ethanol**
  - **Carbon dioxide (from air or vehicle hydrogen reformer) + H_2 → Liquid Fuels**
  - **H_2→H_2**
- **Most options require hydrogen delivered to large chemical plants**
- **Centralized fuel production favors centralized hydrogen production (avoid H_2 collection costs)**

Hybrid Engines for Vehicles

Enabling Technology for Hydrogen-Fueled Vehicles and Connecting Vehicles to the Electric Grid

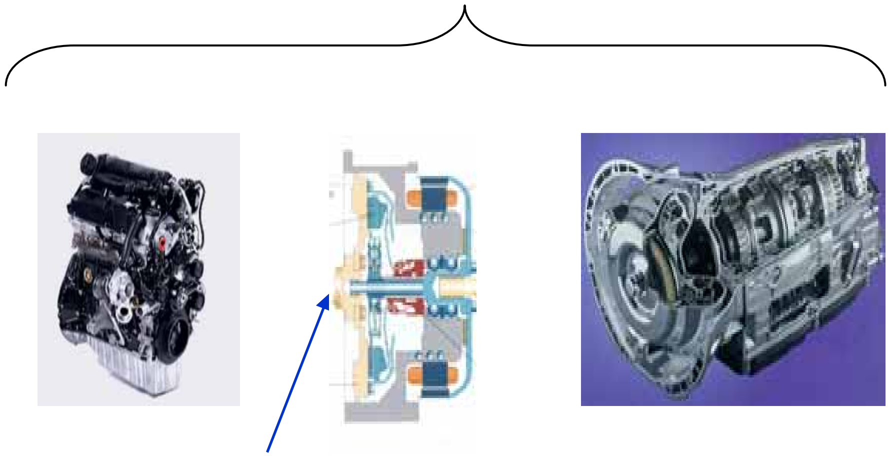
Hybrid Vehicle Engines, a Potential Revolution in Transportation



- **Hybrid vehicle components**
  - **Engine**
  - **Batteries**
  - **Motor**
- **Engine operates at constant speed and load**
  - **Very efficient “base load” engine operation**
  - **Charges battery**
- **Battery**
  - **Provides power when accelerating**
  - **Provides power at low energy demand**
- **Large fuel savings**

Courtesy of the Electric Power Research Institute

Hybrid Vehicles are the Enabling Technology for Hydrogen Vehicles



- **Current engine requirements**
  - **Low cost**
  - **Variable power (0 to 300 Kw)**
- **Hybrid engine requirements**
  - **Low cost**
  - **Constant power ~50 kw**
- **Change in requirements is the enabling factor for hydrogen internal-combustion engines and fuel cells**
  - **Steady-state engines now viable options**
  - **Efficiency more important**

Hybrid Engines May Enable Plug-In Hybrid Electric Vehicles (PHEVs)

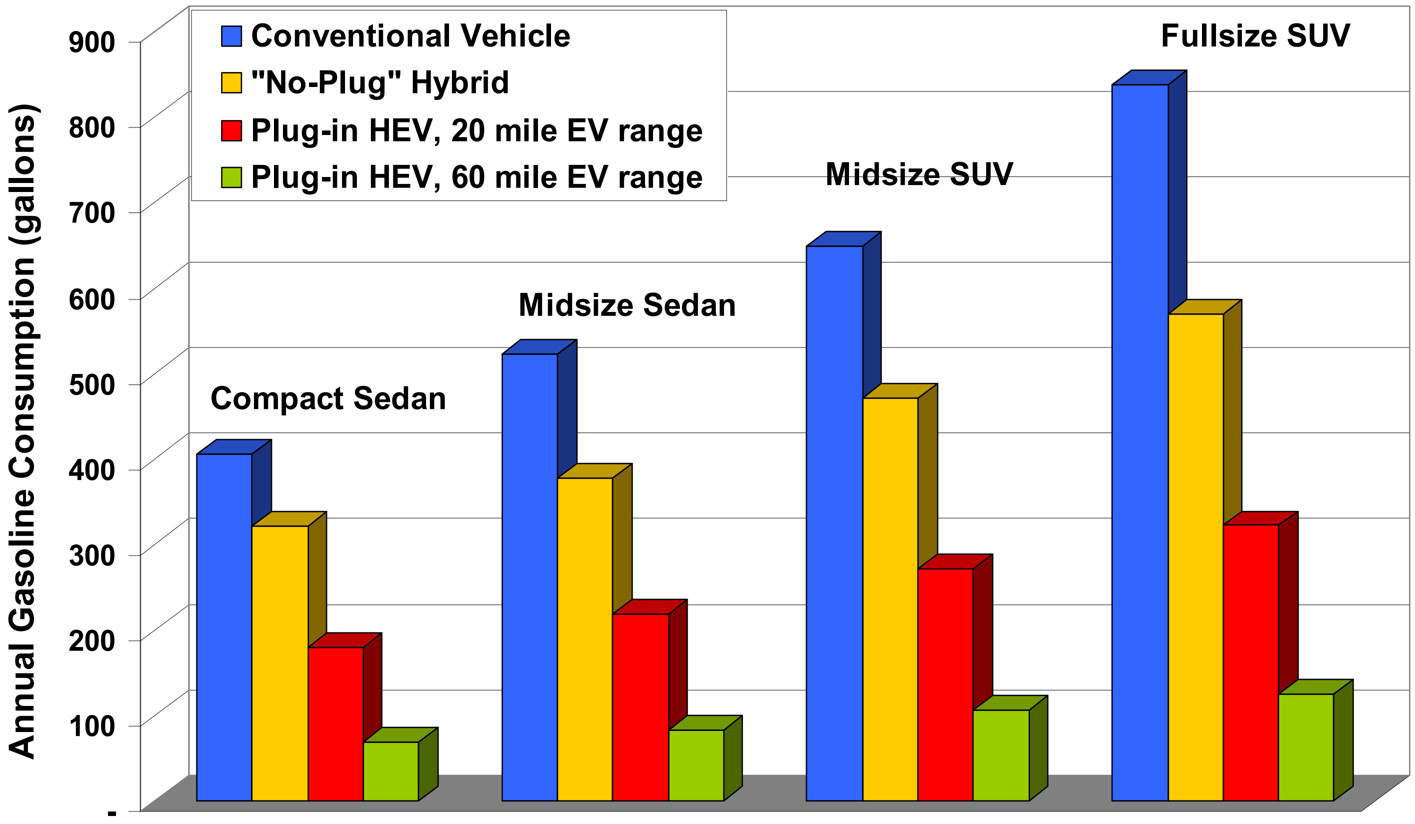
(Recharge Batteries when Vehicle Not in Use)

- **Electric cars have two major battery-connected limitations**
  - **Limited range**
  - **Recharge time (Gasoline refueling rate is ~10 MW)**
- **Hybrid vehicle option**
  - **Electric drive for short trips**
  - **Hybrid for long trips**
  - **Recharge battery over night**
- **Connects cars and light-trucks to the electrical grid**
- **Reduces oil consumption by half or more**

Courtesy of the Electric Power Research Institute

PHEV Annual Gasoline Consumption

Connecting Transportation to the Electric Grid and Nuclear Energy Greatly Reduces Gasoline Consumption



Courtesy of the Electric Power Research Institute

Plug-In HEV Sprinter Van

20-mile electric range on grid electricity

Up to 40% reduction in fuel consumption

Better acceleration than stock Sprinter

15 kWh Lithium Ion advanced battery

120 hp electric motor (up to 280 hp peak)

- **Prototype Plug–In Hybrid Electric Vehicles in testing**
- **EPRI-DaimlerChrysler Van**

Courtesy of the Electric Power Research Institute

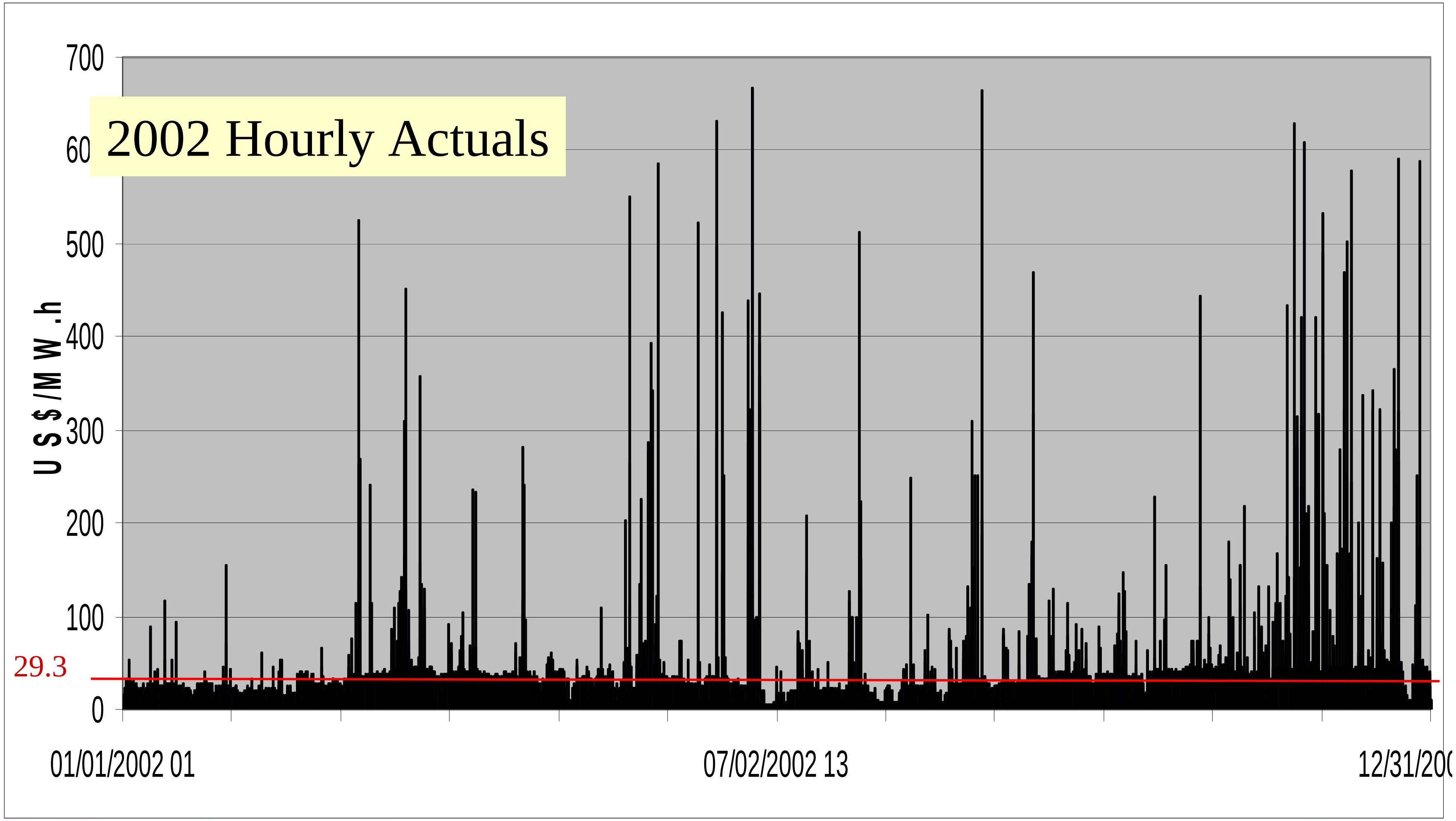
Conclusions

- **Hydrogen is important because it is a way to store energy**
- **Large-scale hydrogen production methods are favored because of the characteristics of hydrogen (atoms) compared to electricity (electrons)**
- **Nuclear energy is the long-term large-scale energy source for hydrogen**
- **Nuclear hydrogen may be the enabling technology for a nuclear-hydrogen renewables energy economy**

BACKUP
BACKUP
BACKUP

Price and Cost of Electricity at Peak Times is Very High

[Alberta Power Pool (US$/MW-h)]



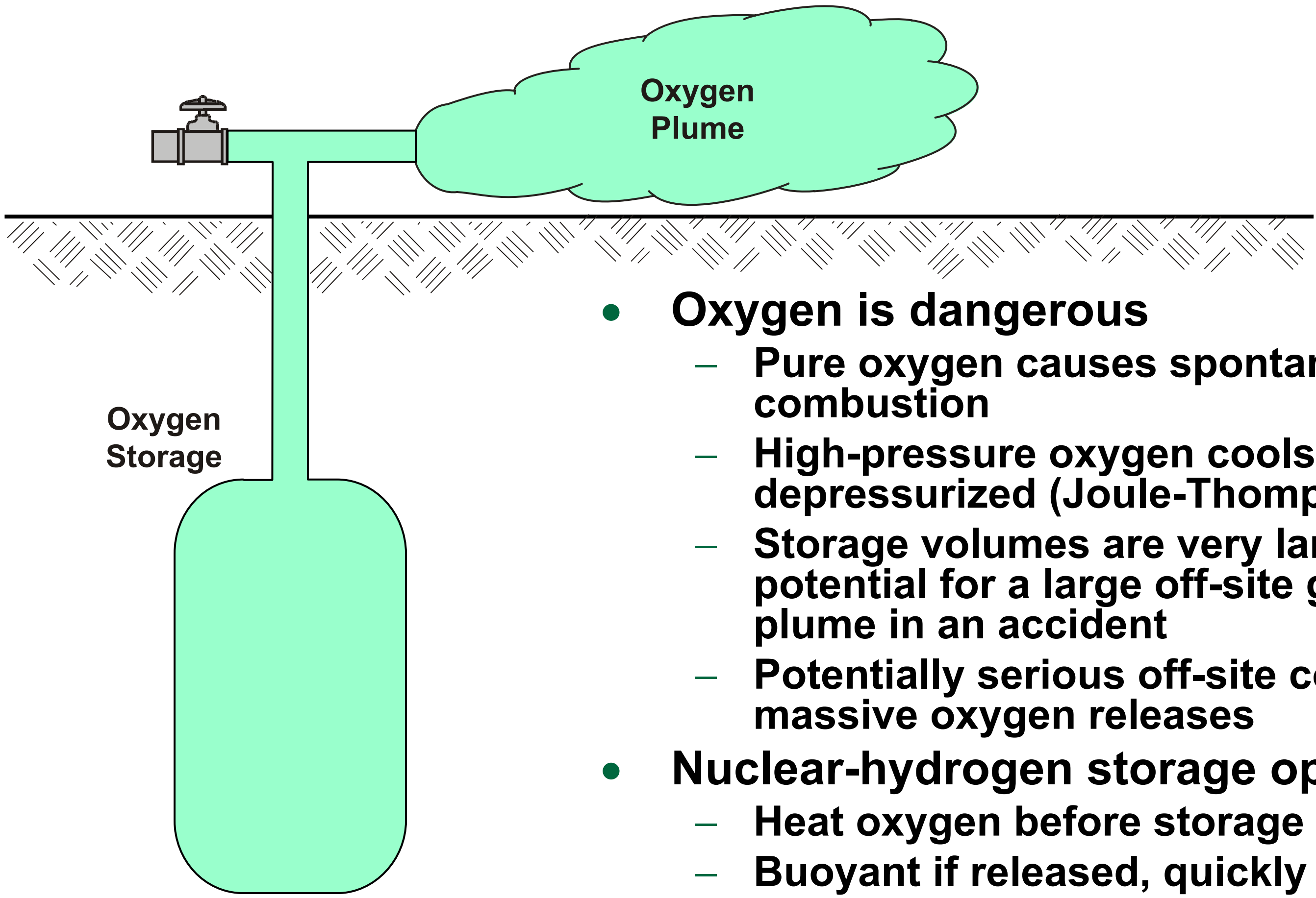
Meeting Peak Power Requirements Implies Large Facilities

Tennessee Valley Authority (TVA) Raccoon Mountain Pump Storage Facility For Peak and Intermediate Power

- **Pump water uphill at night**
- **Water through turbines to generate electricity when there is a high power demand**
- **1530 MW(e)**
- **Effectively a large storage "battery"**

Raccoon Mountain: TVA 1530 MW(e) Pump Storage Facility Powerhouse

Nuclear Heat May Eliminate Oxygen Safety Storage Concerns

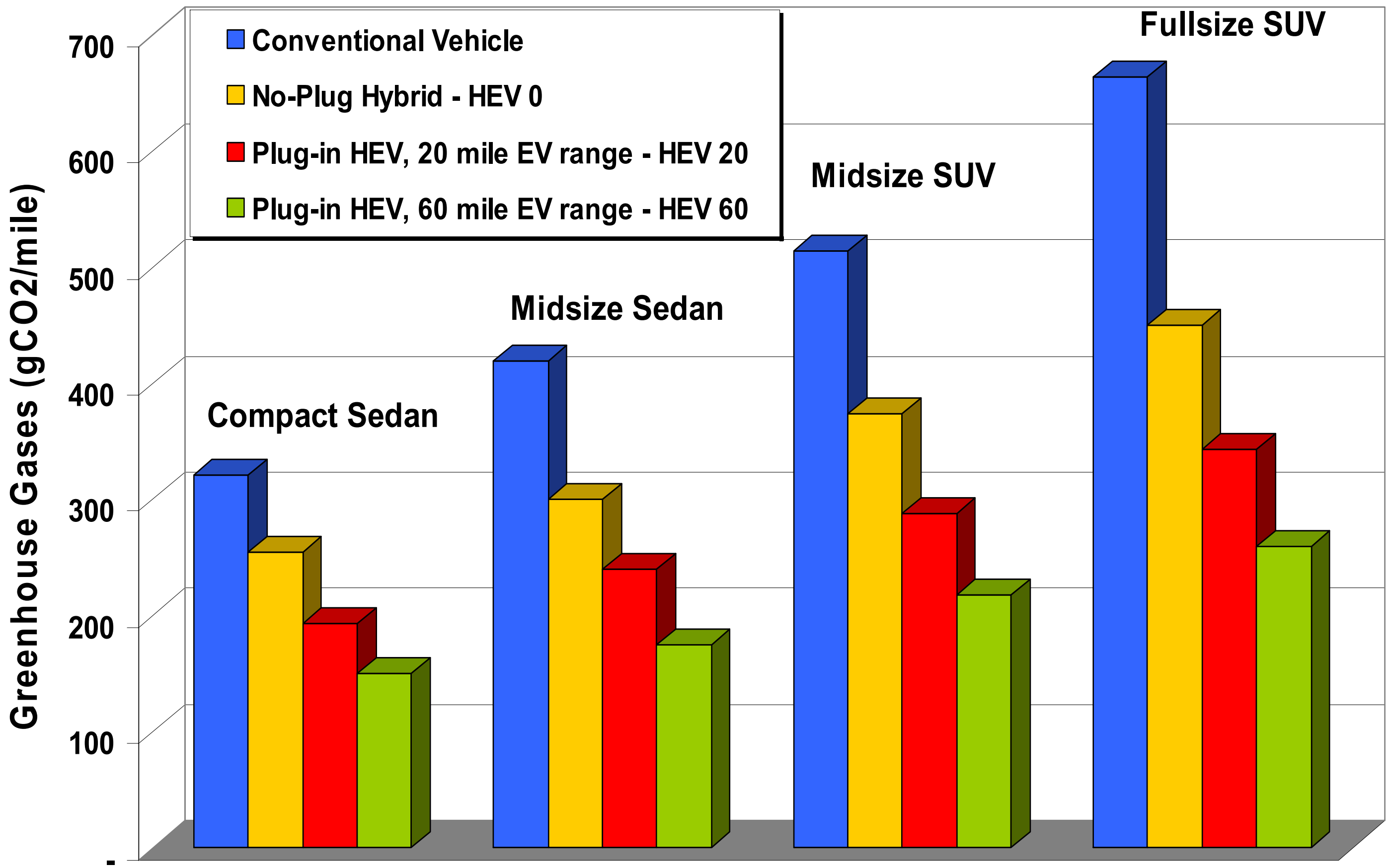


- **Oxygen is dangerous**
  - Pure oxygen causes spontaneous combustion
  - High-pressure oxygen cools when it is depressurized (Joule-Thompson effect)
  - Storage volumes are very large with the potential for a large off-site ground-level plume in an accident
  - Potentially serious off-site consequences if massive oxygen releases
- **Nuclear-hydrogen storage option**
  - Heat oxygen before storage by 20 to 40ºC
  - Buoyant if released, quickly diluted
  - No off-site risk
  - Viable with nuclear heat

Not All Hydrogen Futures Require Vehicle Storage of Hydrogen
(Carbon Dioxide Separating Reformer)

- **Fuel + Carbon Dioxide Separating Reformer → Hydrogen + Calcium Carbonate**
  - $CH_4 + H_2O \rightarrow 3H_2 + CO$
  - $CO + H_2O \rightarrow H_2 + CO_2$
  - $CaO\ (s) + CO_2\ (g) \rightarrow CaCO_3\ (s)$
- **Carbonate is recycled with fuel production**
  - $CaCO_3\ (s) + 4\ H_2\ (g) \rightarrow CaO\ (s) + CH_4\ (g) + H_2O$
- **Notes**
  - **Low fuel system weight**
  - **Central use of hydrogen**
  - **Y. Kato, Japan patent 2001-3054 (Applied Jan 10, 2001)**

Well-to-Wheels Greenhouse Gas Emissions for Different Options



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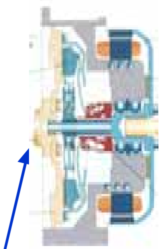
Hybrid Sprinter, One Way to the Future

Technical solution/construction set/ modular scaling concept

Plug-In Hybrid (Dual mode: Hybrid mode and pure electric mode with a range of 20 miles)
- Consumption reduction
- Local emissions free
- Customer: Distribution and service vehicles
- System weight ~160kg–350kg

Basic vehicle		Van 3.5t/3550mm
	combustion	5-zyl. Diesel
	transmission	Automatic W5A380
	torque/power	330Nm / 115kW
	weight	1960kg
E-Motor		
	torque (peak)	180 Nm (275Nm)
	power (peak)	70kW (90kW)
Battery	**NiMH / Li-ion**	
	capacity	14kWh / 14kwh
	weight	ca. 300kg / 160kg
Fuel reduction		
	NEDC	-23%
	AMS	-10%
	EPRI study	-55%
Emission reduction		
	NEDC	-100%*
Acceleration		
	0..100km/h	ca 22sec



Diesel OM647 | **Clutch** | **E-motor 70kW** | **Transmission** | **Plug**

Courtesy of the Electric Power Research Institute

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