Coupling Carbonless Electricity and Hydrogen Transportation

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Present Challenges and Future History: global energy use may quadruple over 50 years according to Shell's sustained growth scenario

Today:

Near-term concerns merit moving toward hydrogen

- zero tail-pipe emissions
- national security: universal availability
- economic security: vehicles, fuel, and utilities are critical industries
- economic integration of renewable intensive & decentralized transportation and utility sectors

QuickTime™ and a TIFF (PackBits) decompressor are needed to see this picture.

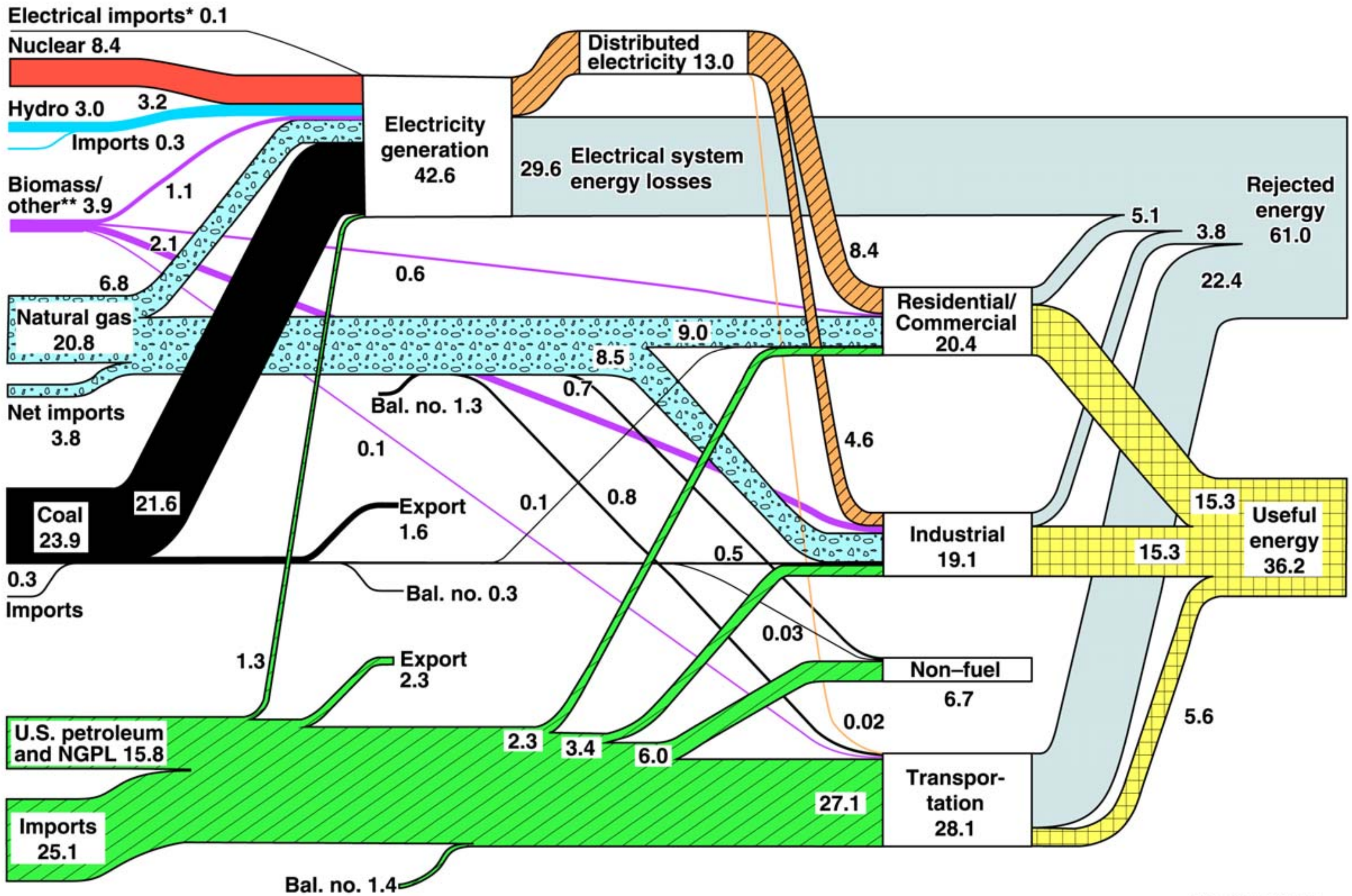
20 TW

Tomorrow:

Energy carriers will be hydrogen and electricity

- food,land, and water will limit biomass
- atmosphere will limit carbon emissions
- security will limit economic oil and gas

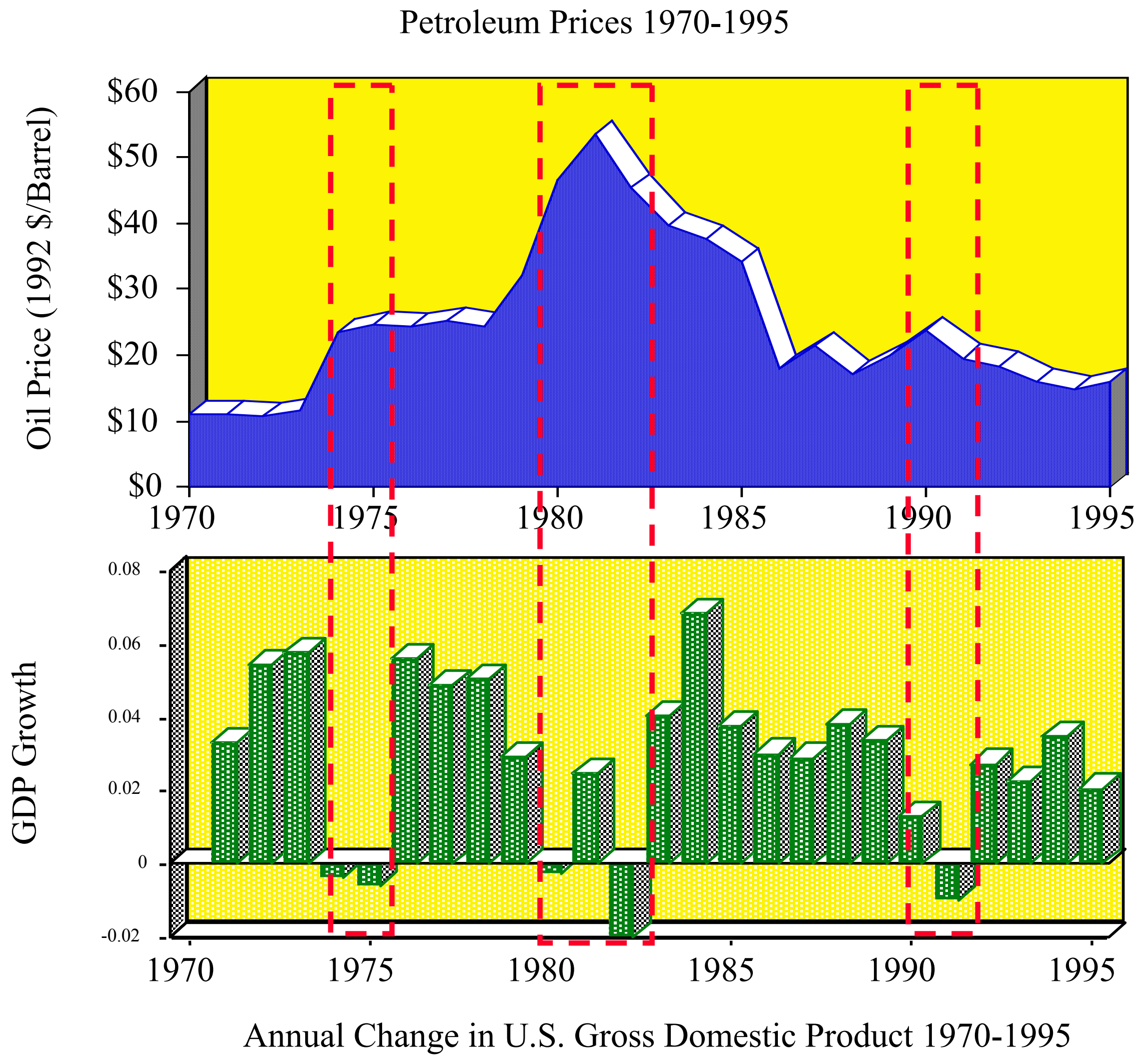
2000 U.S. Energy Flow is 104 EJ/yr (3.3 TW) but Electricity is only 3.6 Trillion kWh (0.4 TW) (30% eff.)



Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2000*
*Net fossil-fuel electrical imports
**Biomass/other includes wood and waste, geothermal, solar, and wind.

December 2001
Lawrence Livermore National Laboratory
http://en-env.llnl.gov/flow

Energy/economic security has been a critical challenge each recession in the last 3 decades - costing trillions - has been associated with oil price shocks



Source: EIA 1995,1996

U.S. highway oil consumption is projected to grow from twice to three times domestic oil production by 2020

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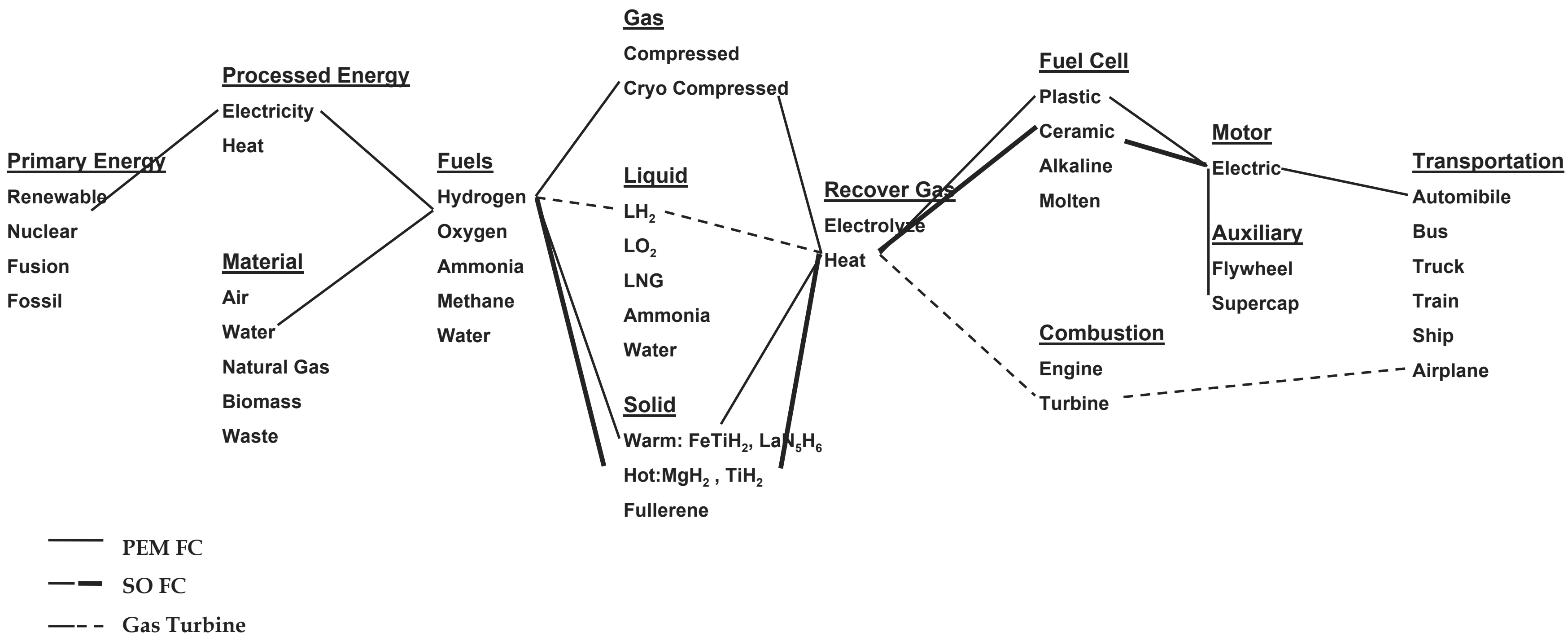
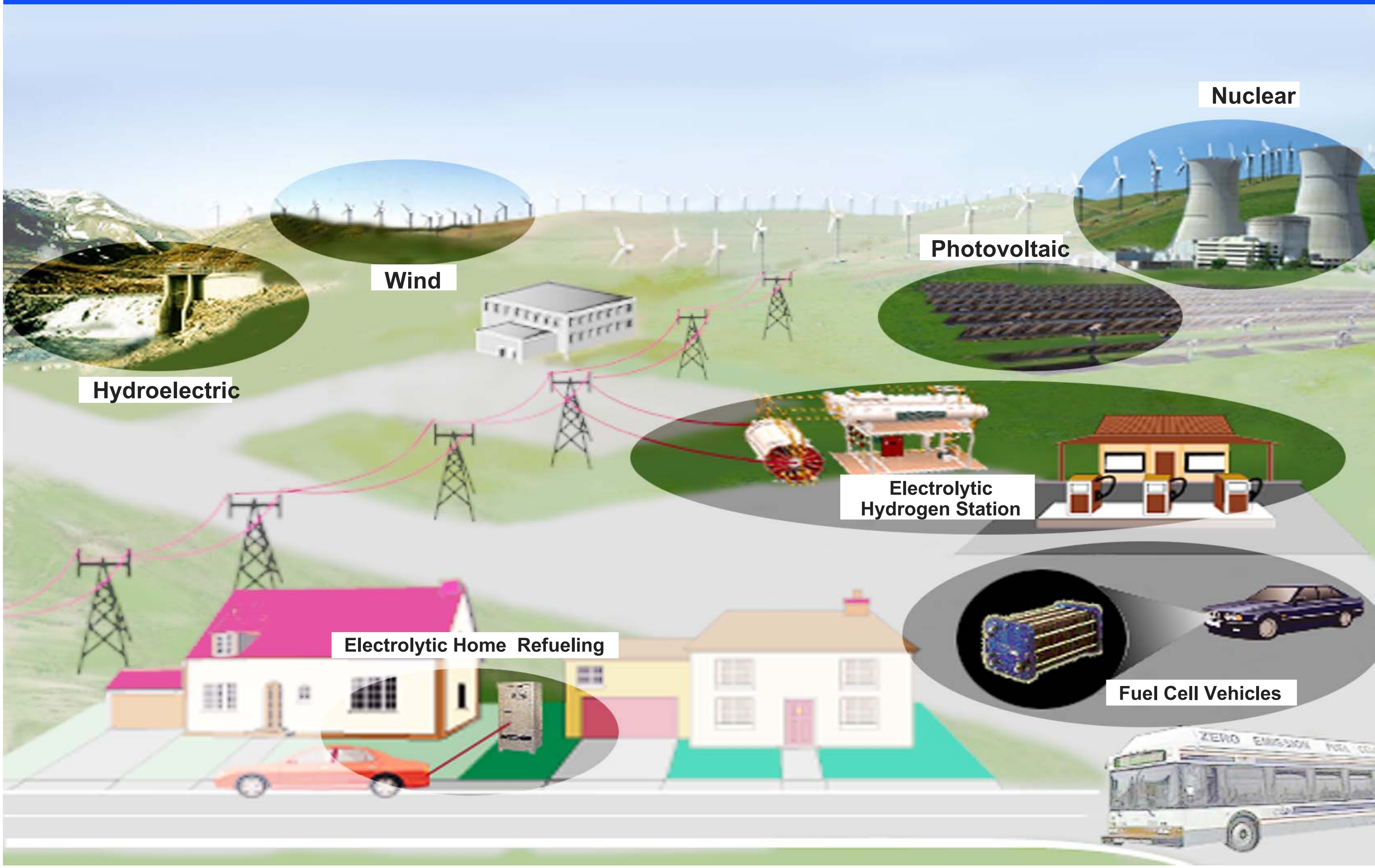
Myriad (future) replacements for oil can be envisioned



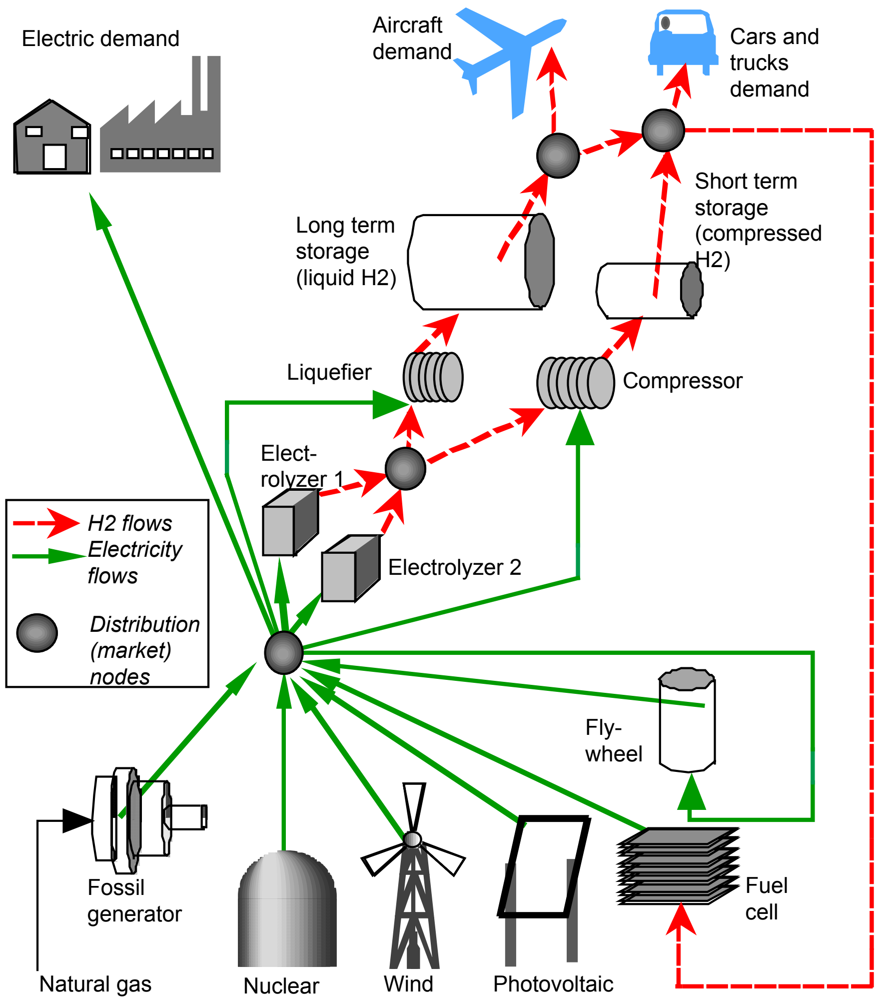
H_2 is just one of many potential synthetic fuels but also the *majority* component and production precursor for them all

QuickTime™ and a TIFF (PackBits) decompressor are needed to see this picture.

H_2 is uniquely capable of *dynamically* linking carbonless electricity and transportation through electrolysis of H_2O



Distinct from fossil fuels, H_2 is not an energy source, H_2 instead carries energy from primary sources



H_2 Utilization
(transportation fuel)

H_2 Storage
(gaseous & cryogenic liquid)

H_2 Production
(electrolysis)

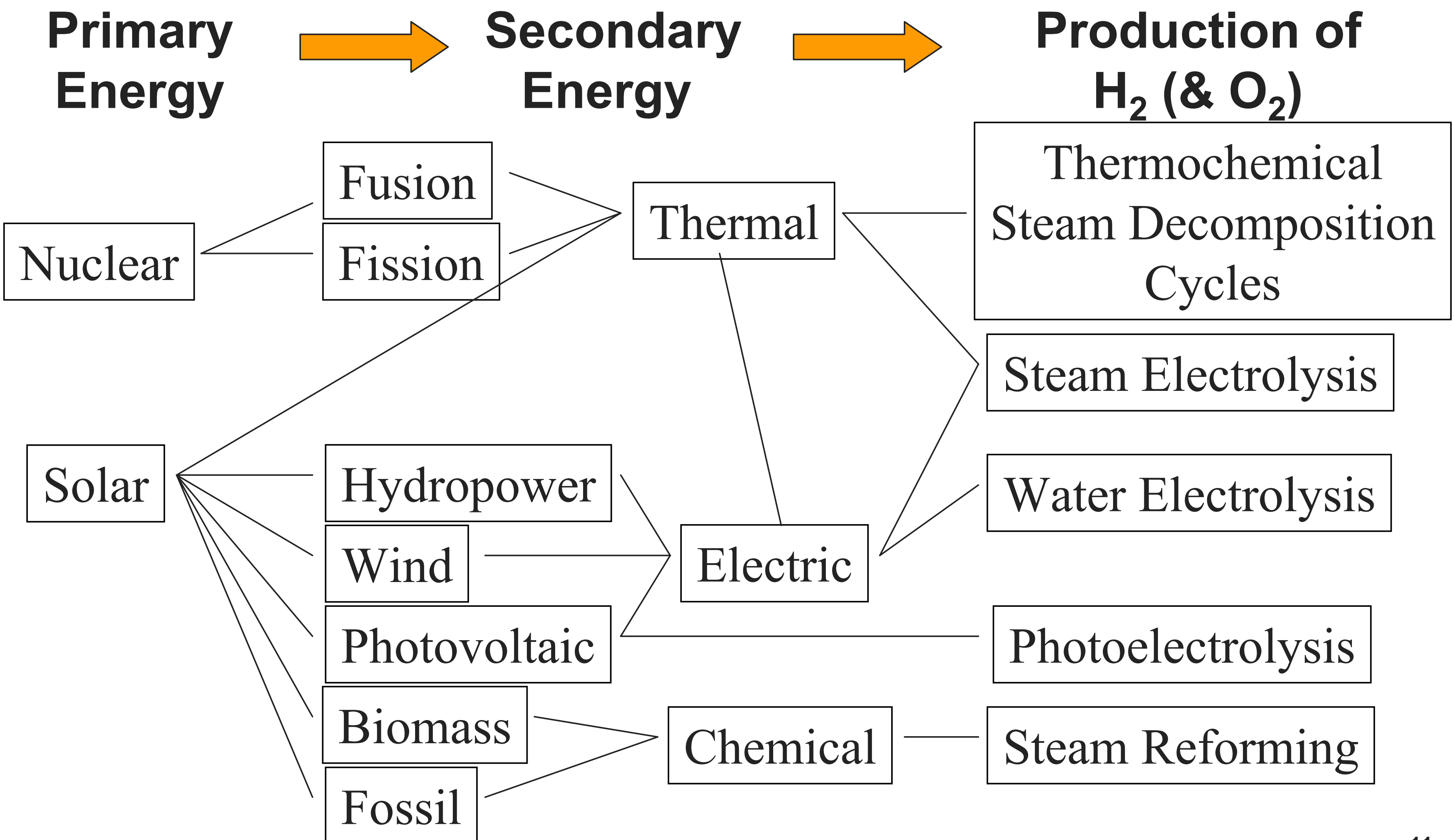
Electricity Generation
(*r*egeneration by fuel cell)

Primary Energy
(fossil or non-fossil)

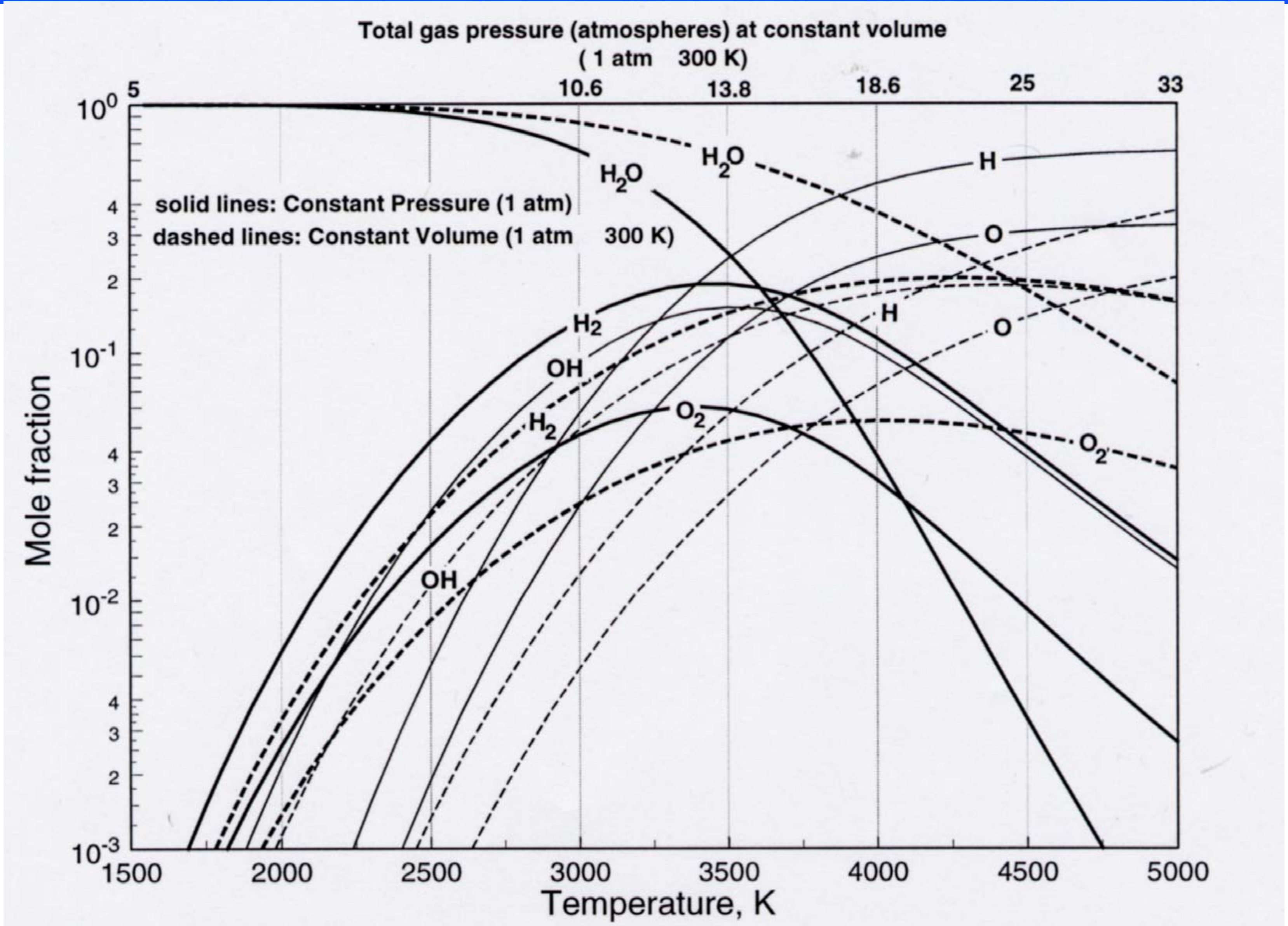
Strategic advantages of H_2 as an energy carrier

• **Clean**	***non-toxic*, made from (and returns to) H_2O**
• **Carbonless**	**Zero emissions (e.g. *greenhouse* gases)**
• **Universal**	**Feasible for *all* transportation modes (air, land,sea)**
• **Versatile**	**H_2 can carry energy from *any* source (electricity)**
• **Synergistic**	***Dynamic* integration of electricity & transportation**
• **Transitional**	**Smooth, scalable, flexible infrastructure *evolution***
• **Ultimate**	**H_2 is simple, pure, light, efficient, *final***

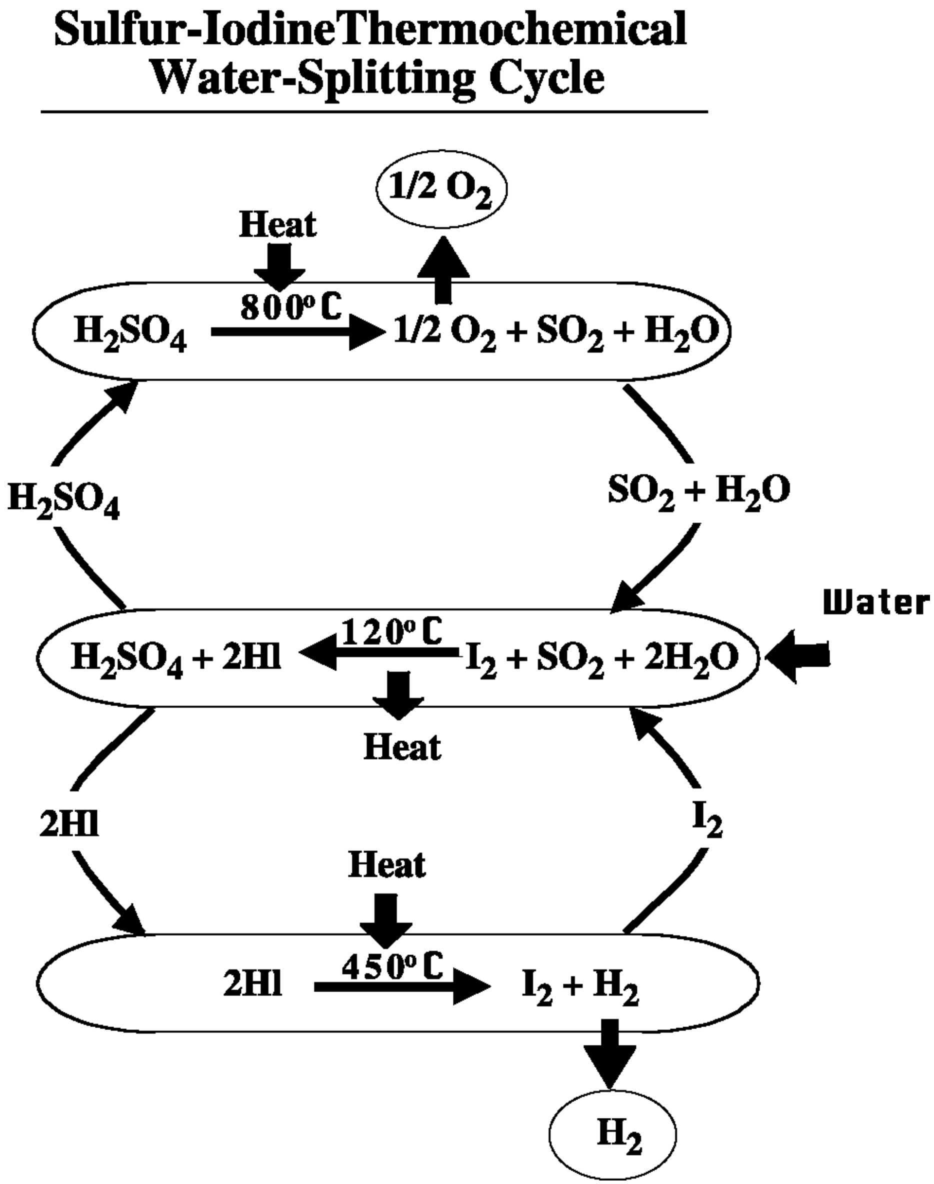
H_2 production fundamentally requires decomposing H_2O into H_2 and O_2 by myriad methods but all use thermal, electric, or chemical energy



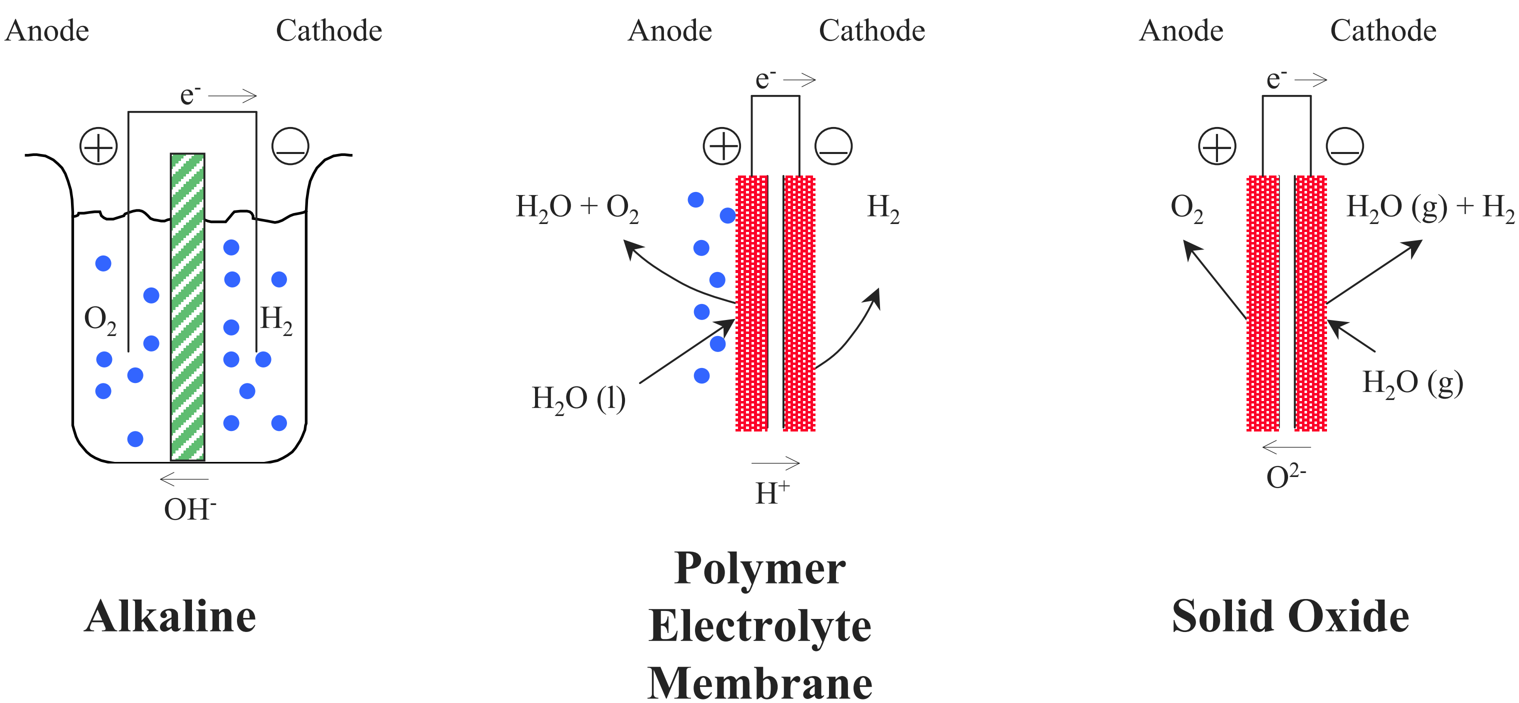
Direct thermal decomposition of H_2O is hampered by the thermodynamic equilibria of steam. T > 2500 K is needed but H_2 and O_2 also decompose at these high temperatures



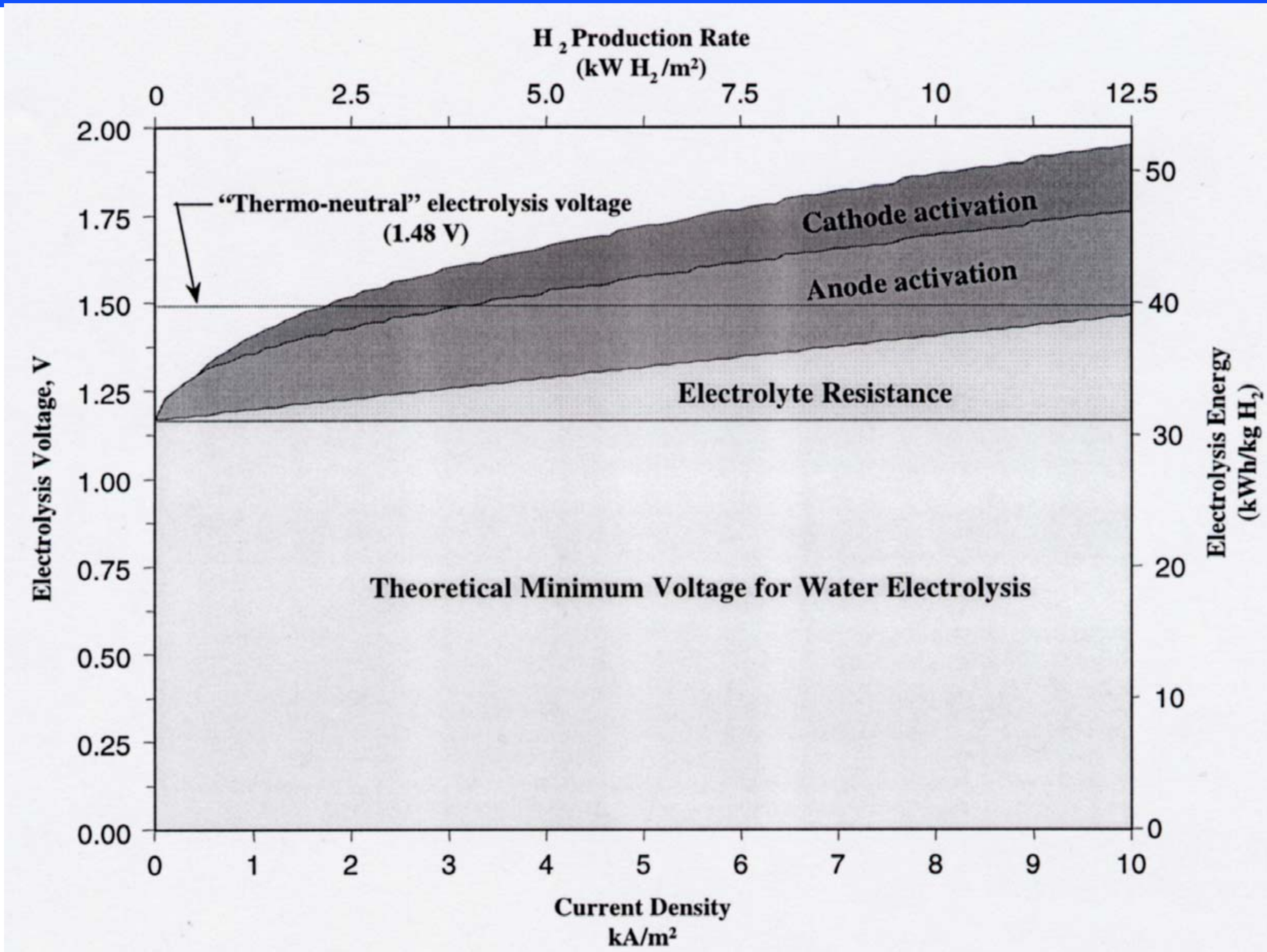
Multi-step thermochemical H_2O decomposition reduces peak temperatures, but also lowers Carnot efficiency GA claims HTGR S-I cycles can achieve ~42% (50% HHV)



Electrolytic H_2 production technologies are fundamentally distinguished by choice of ion (OH^-, H^+, O^{2-}) to be conducted across the electrolyte



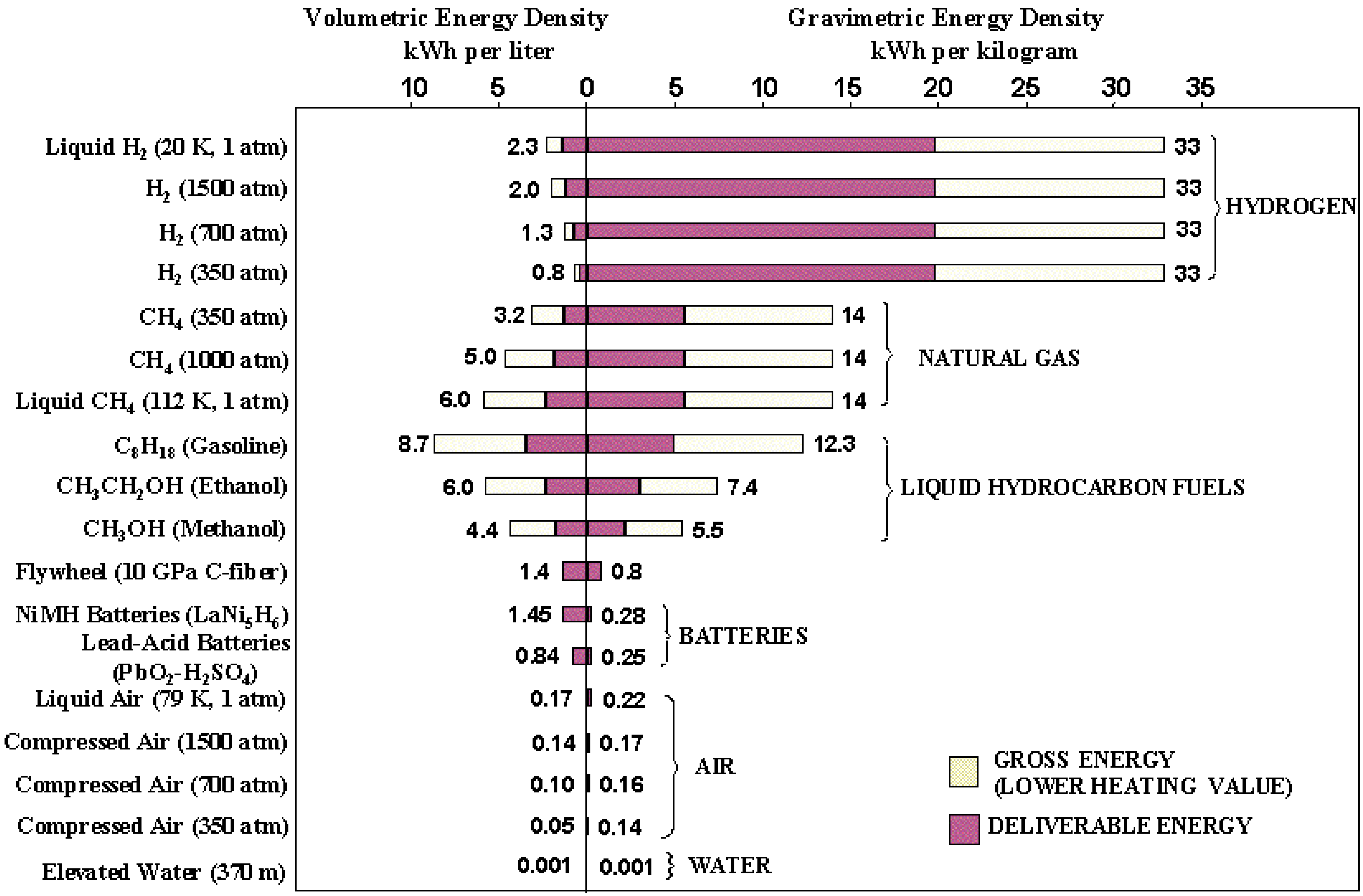
Conventional alkaline (KOH) electrolysis theoretically requires 1.23 Volts but 1.48 V (83%)to be thermoneutral and ~1.9 V (65% or 50 kWh/kg H_2) at high current density



Electrolysis thermodynamics mean high water (steam) temperatures and pressures reduces theoretical voltage - if *both* heat and electricity are available

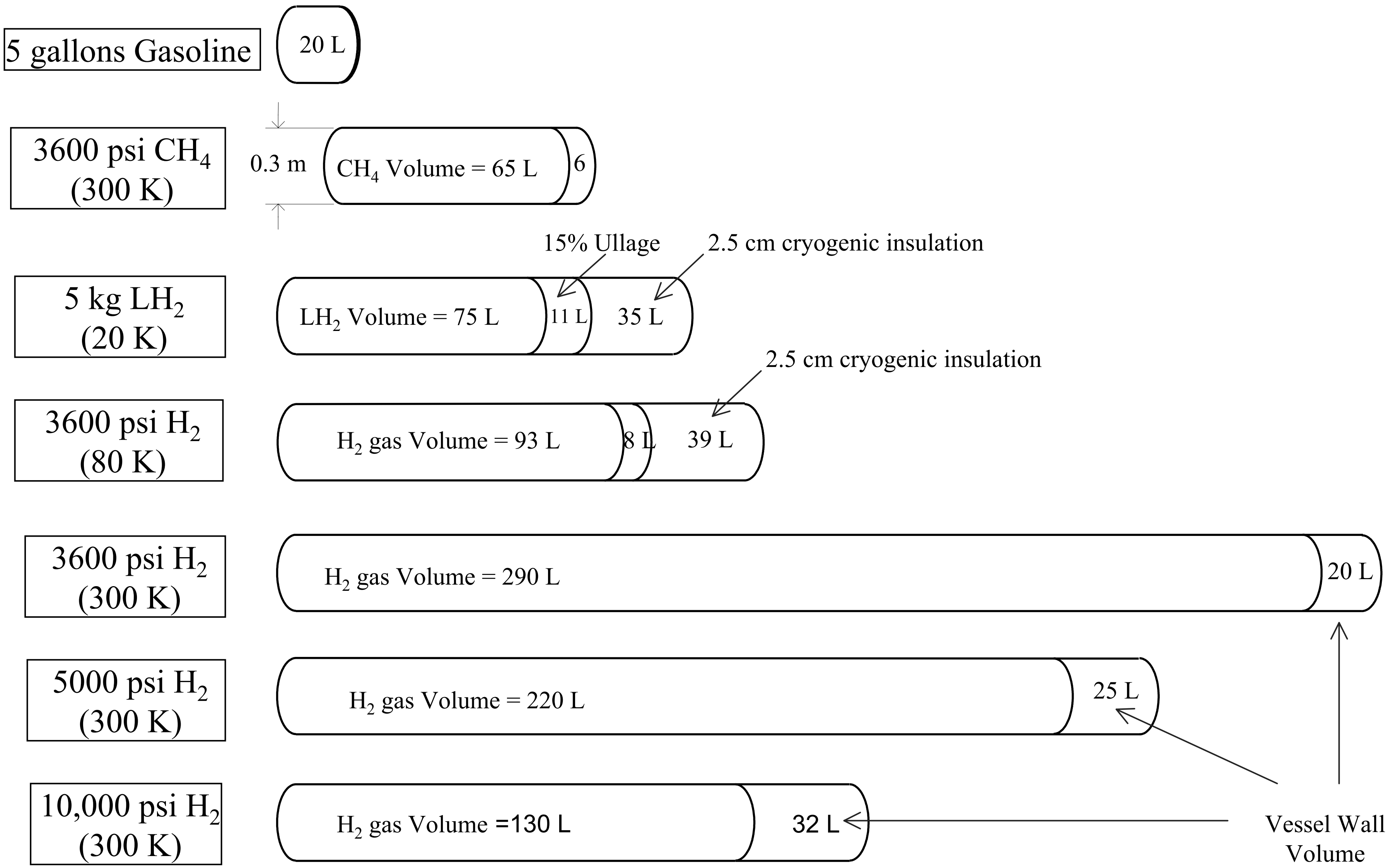
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

On an equal energy basis H_2 is the *lightest* - but also the *least compact* fuel magnifying storage vessel mass, volume and cost



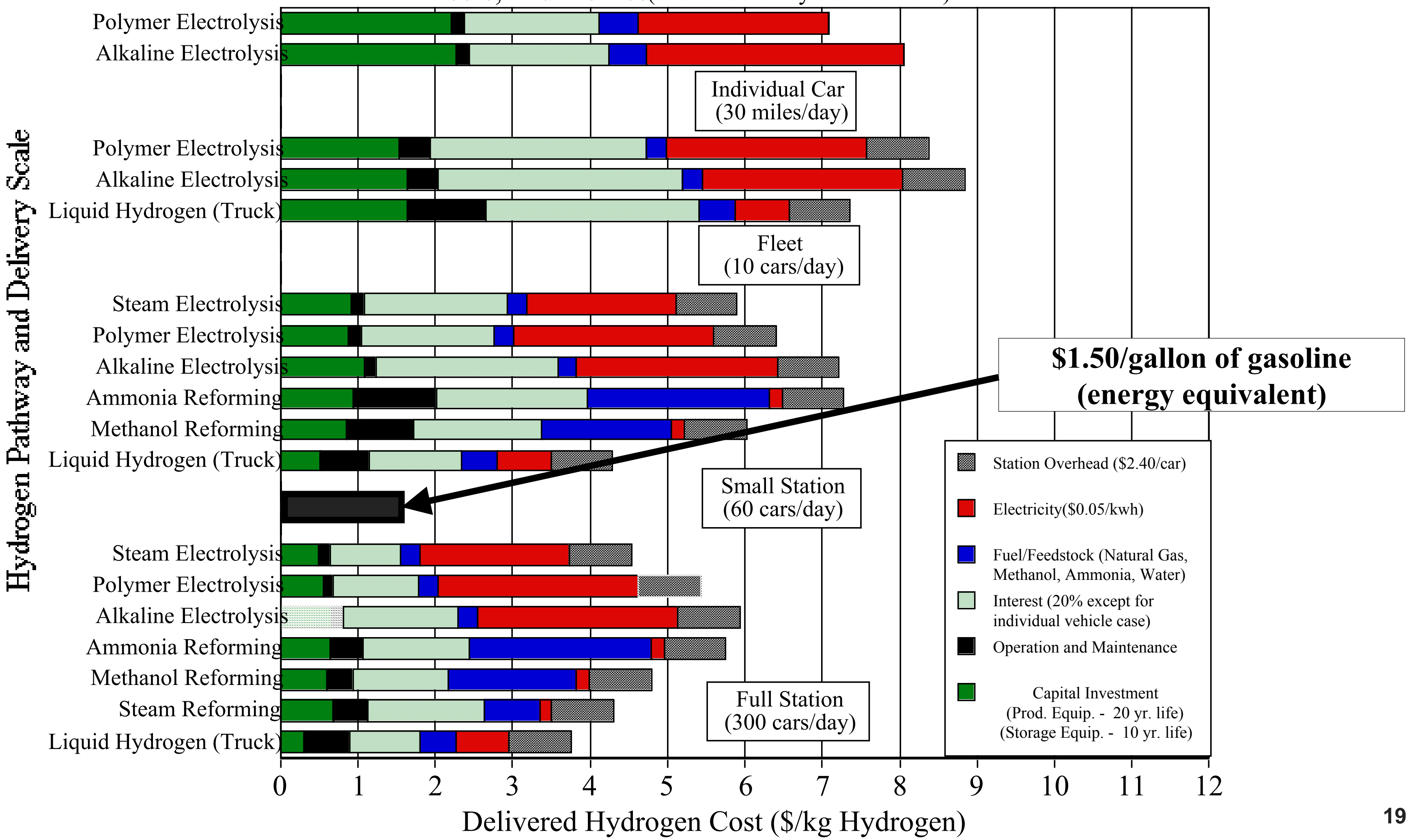
Vessel walls, insulation, and LH_2 thermal expansion limit volumetric efficiency of high density H_2 storage

(all volumes shown store 5 kg H_2 or energy equivalent)



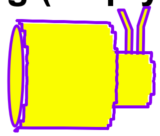
H_2 will cost more than fossil fuels as long as the *energy* to produce & store H_2 costs more than fossil fuels

Figure 8. Cost Breakdown of 7 Hydrogen Pathways for Stations, Fleets, and Homes(broken down by cost element)



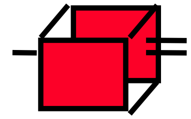
The expense and volume of H_2 can (only) be overcome by high efficiency (60-100 mpg or 25-40 km/L) vehicles using *only* ~ 5 kg of H_2 for 300-500 mile (480-800 km) range

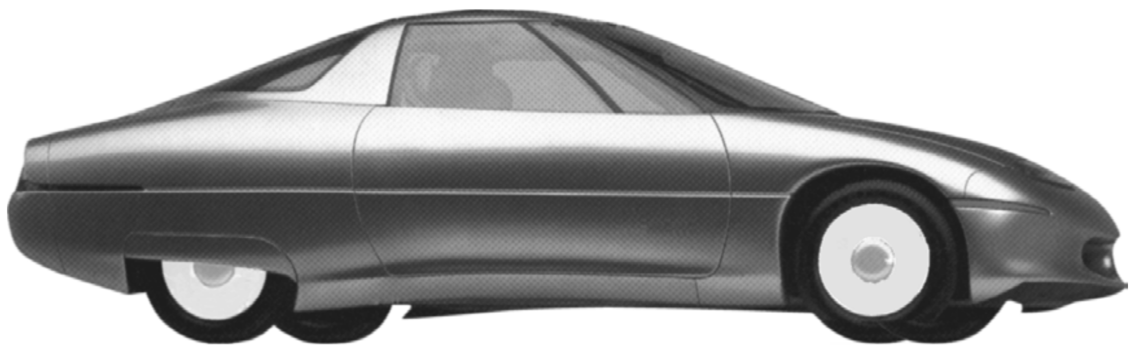
Electric drive motor: 80 kW maximum power
Body and frame - C_d = 0.2; 1100 kg (empty wt)
Cross-sectional area: 2.0 m^2
Regenerative braking
35km/L energy equivalent
(0- 60 mph < 10 sec.)



PRIMARY ENERGY CONVERSION:

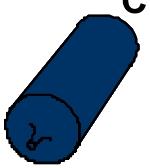
30 kW fuel cell



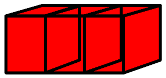


HYDROGEN STORAGE:
5 kg/400 mile range

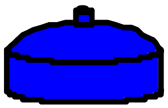
Compressed H_2
(5,000-10,000 psi)



Cryogenic (Insulated)
Pressure Vessel
(20- 80K)

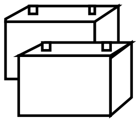


Metal hydride "sponge"
<100 psi, < 100C



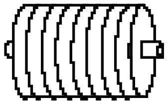
Liquid hydrogen tank
(50 psi, 20- 28K)

PEAK POWER (2 kWh)



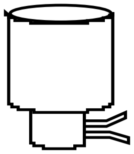
Advanced Batteries

or



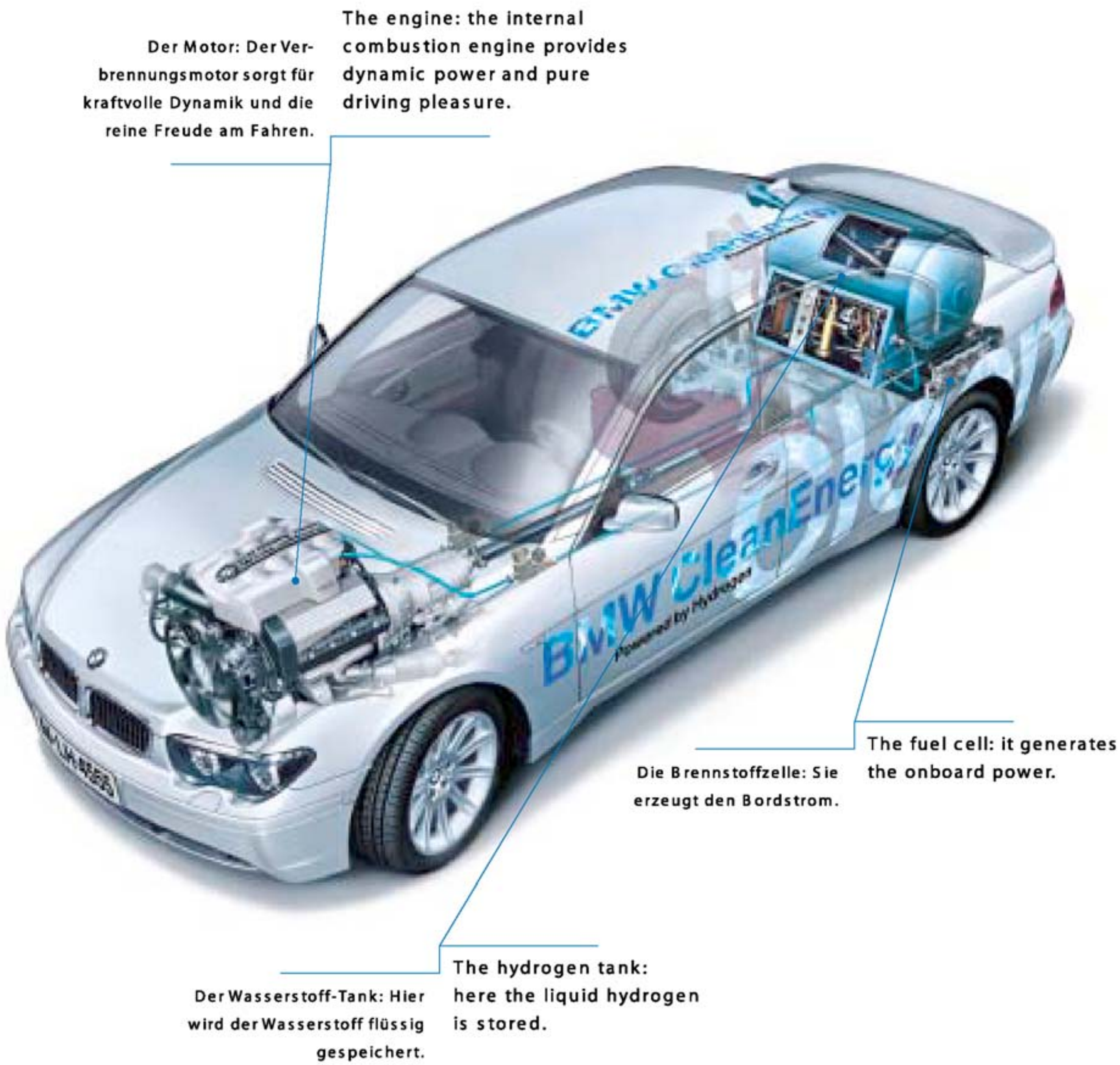
Ultracapacitors

or



Advanced Flywheel

BMW has prototyped 5 generations of LH_2 cars A fleet of 15 dual-fuel vehicles have been road tested > 100,000 km



300 km LH_2 range

+

650 km gasoline range

A robotic LH_2 refueling station has been demonstrated

Hydrogen as Alternative Fuel

filling stations - the ROBOT application -

Linde AGA

www.Linde.com

Drive in, check in & positioning of the robot Ö

... opening of gas cap ...

Ö po sitioning of the coupling Ö

... filling / refilling of the LH_2 tank system.

Linde AG, Linde Gas
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wolf, sde, 1760, Fach 60
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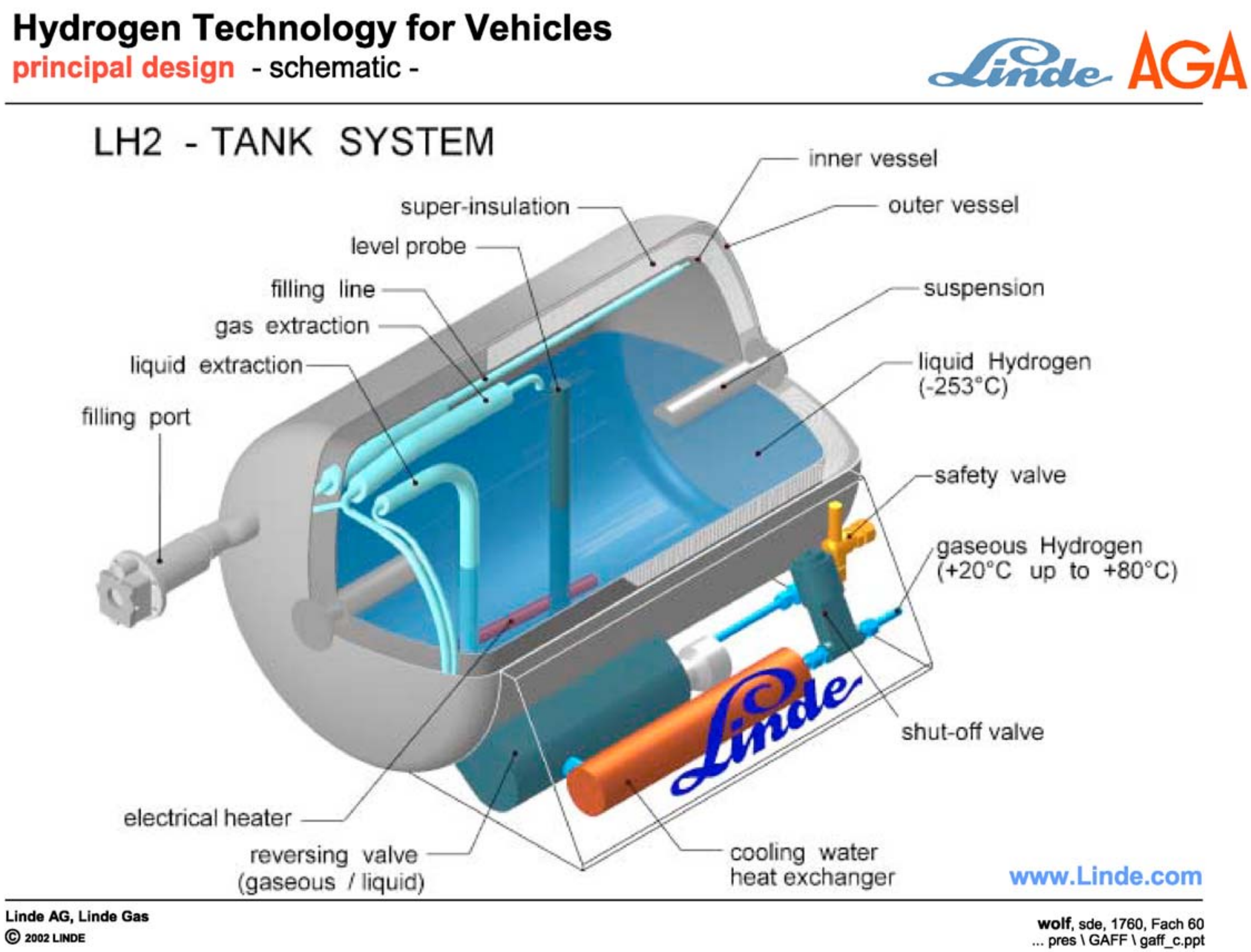
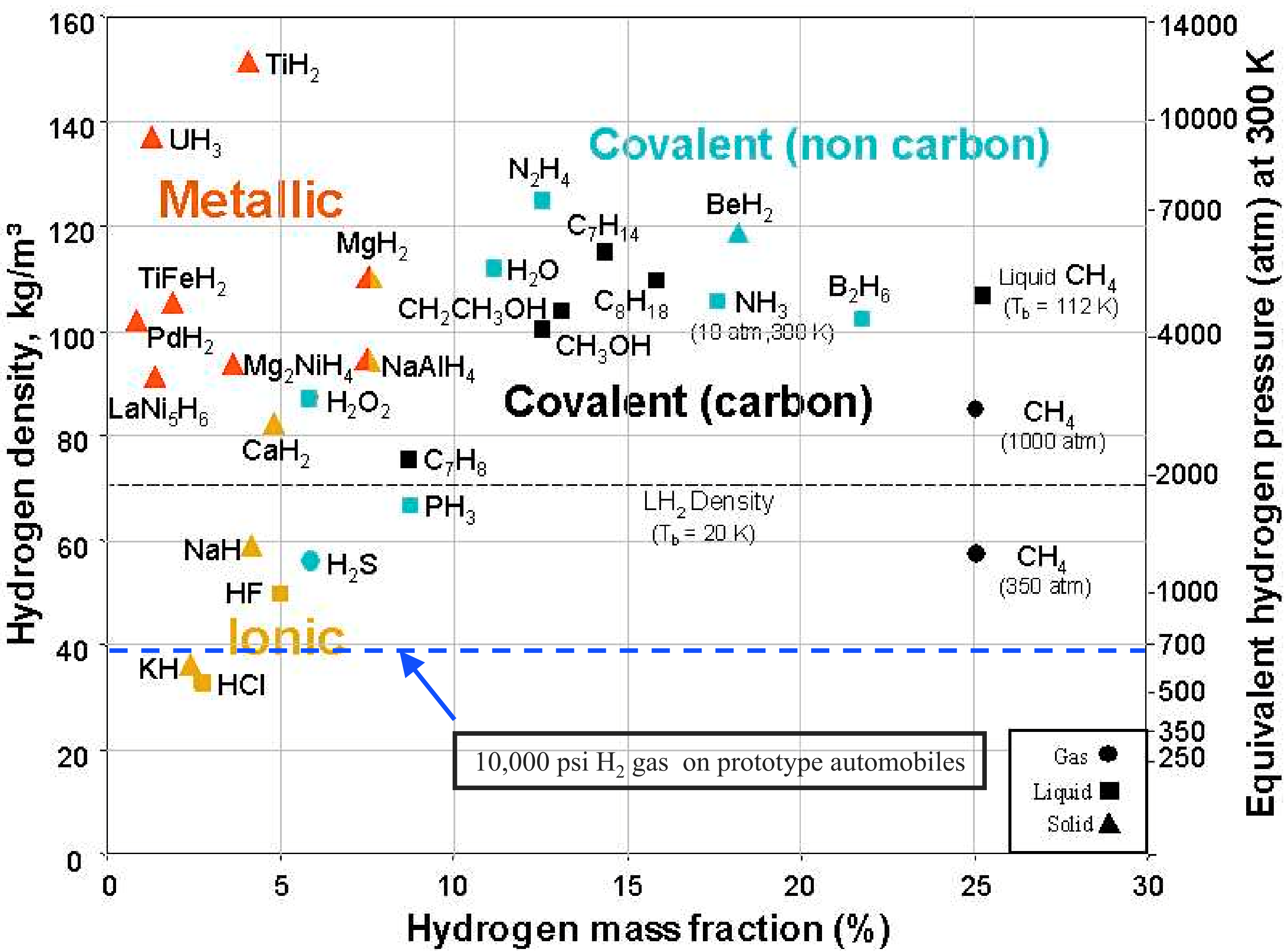
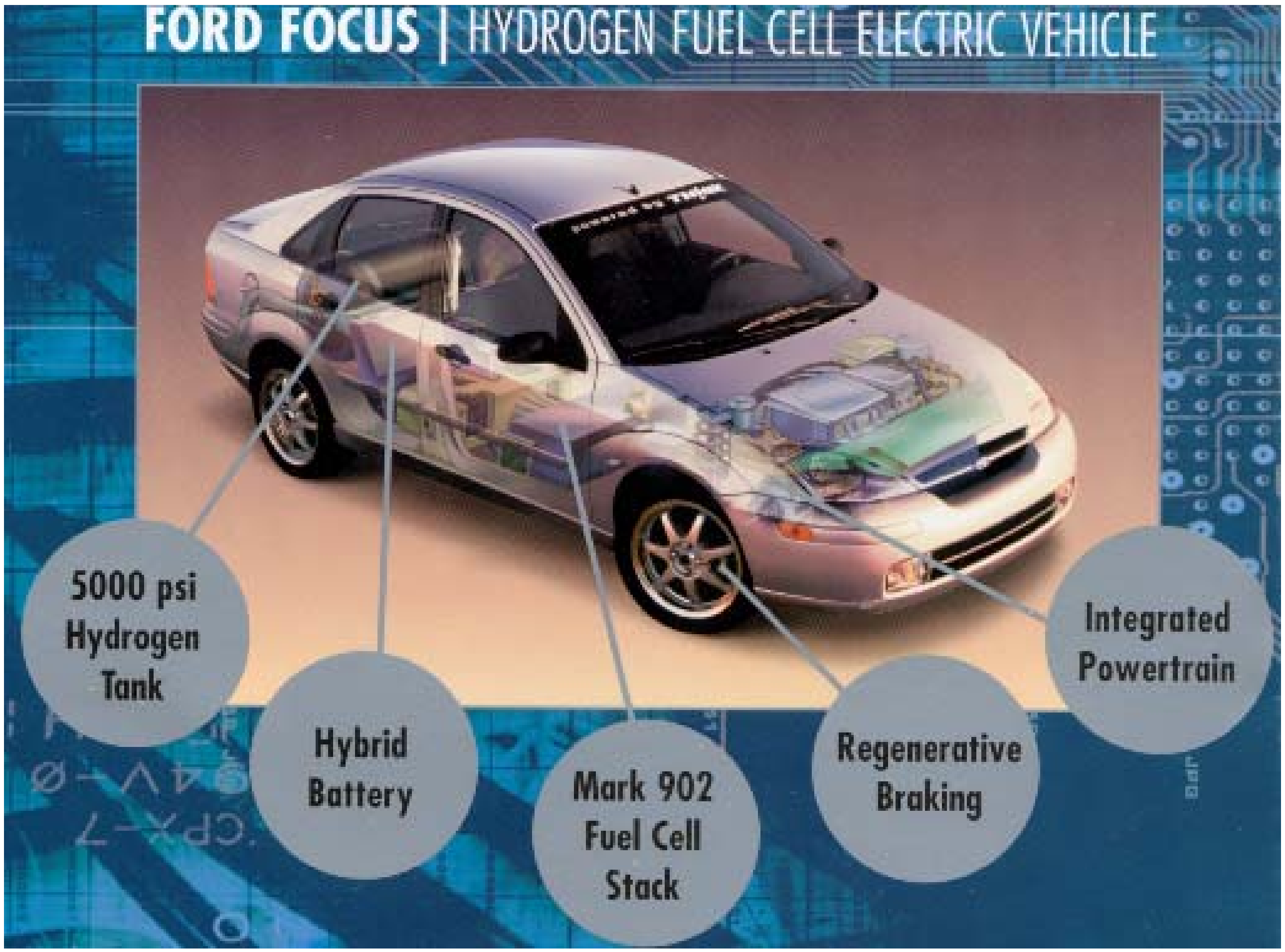
LH_2 storage is lightweight and routine for spacecraft but Liquefaction is energy intensive (10 kWh/kg LH_2 or 30%) LH_2 requires heat transfer below 1 W to remain cold (~1 week)



Covalent H_2 compounds are more compact than LH_2 but are hazardous (NH_3) or use carbon (CH_4). *Ionic* & *metallic* hydrides are either heavy or release H_2 only when very hot



U.S. automakers have developed concept/prototype cars in the past 2-3 years. Each stores 5-10 ksi compressed H_2



4 kg H_2 @ 5000 psi

Fuel-cell Battery Hybrid

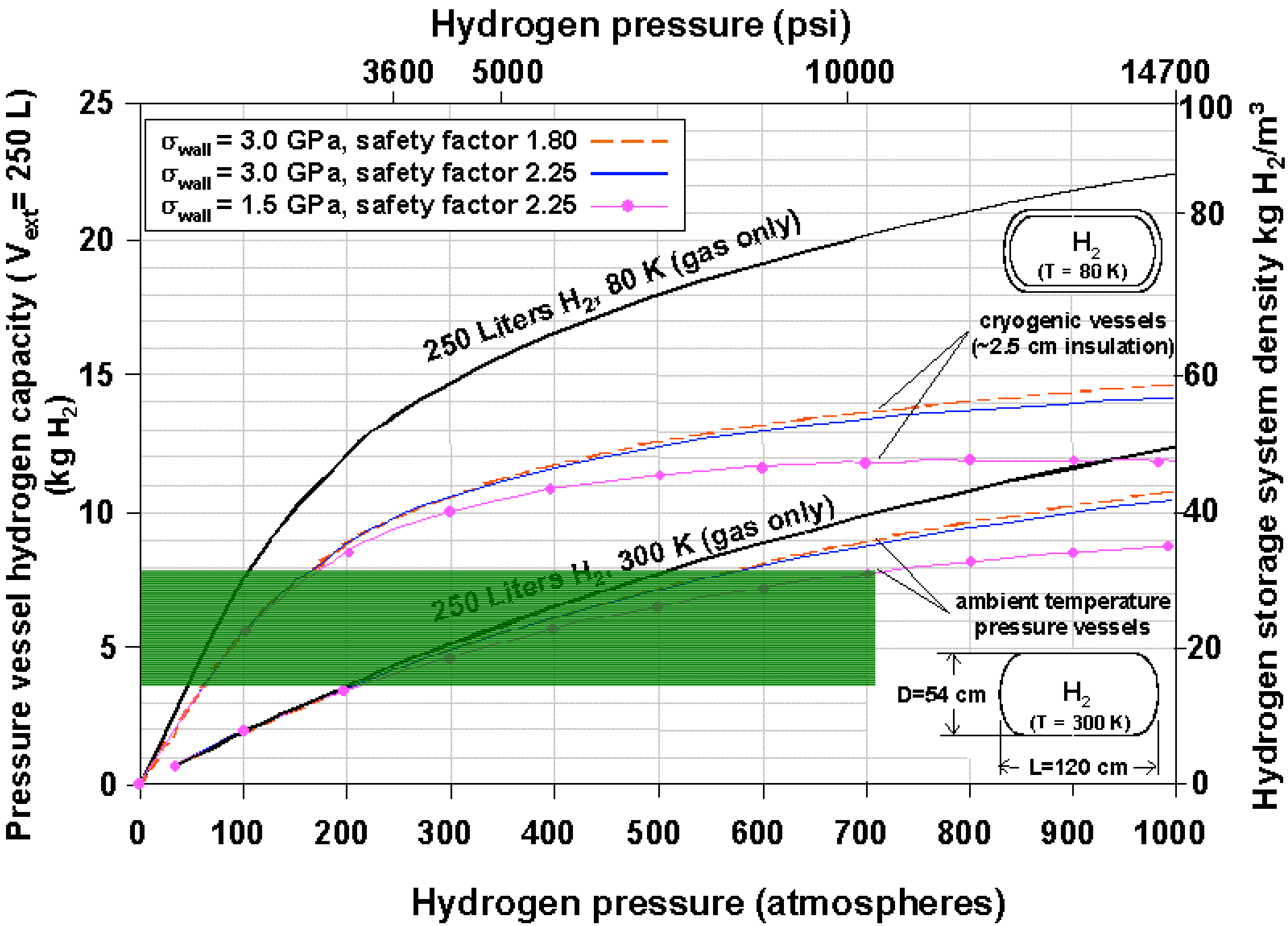
60-70 mpg

240-280 mile range

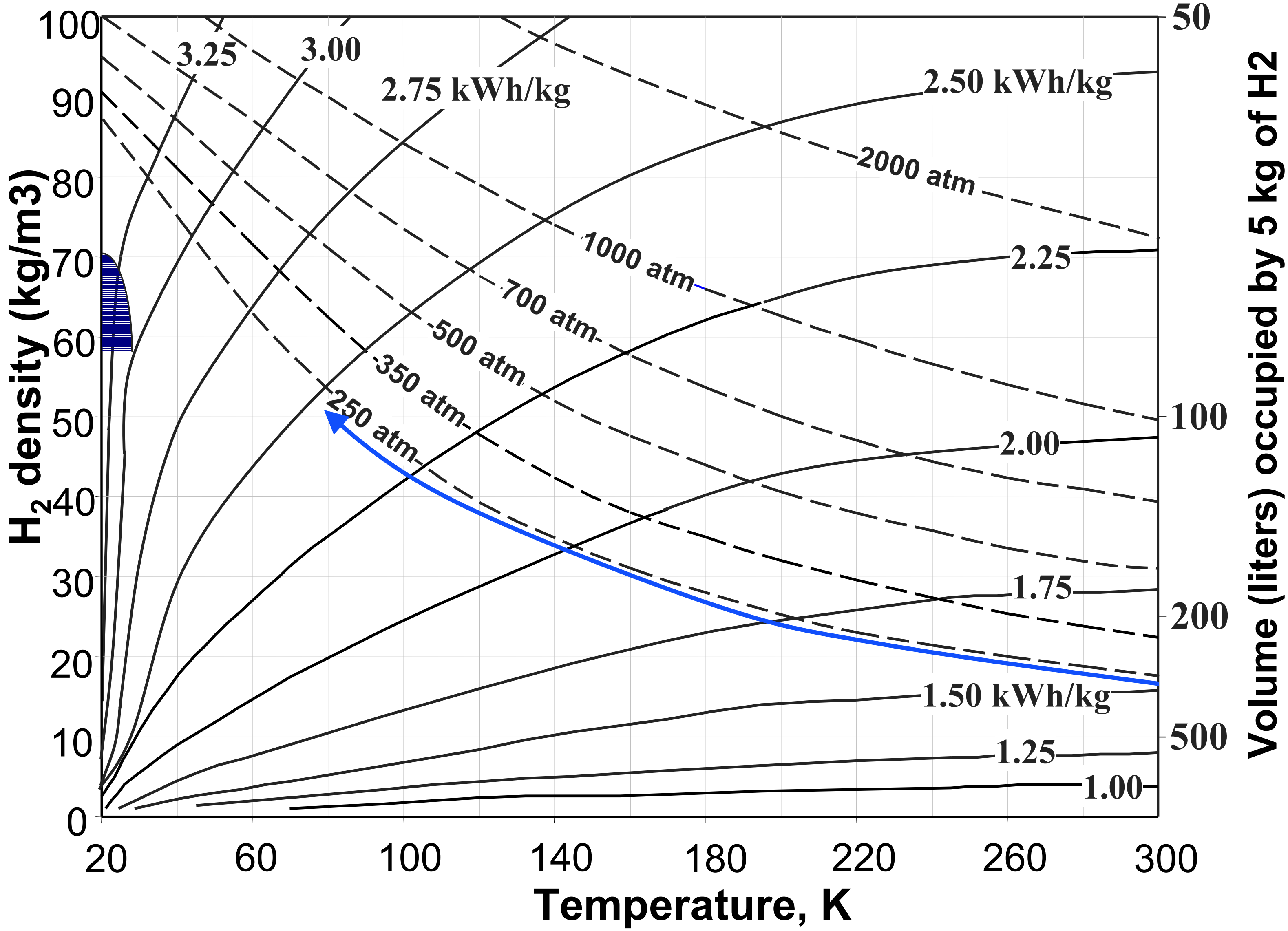
GM's prototype chassis height is 6-12 *inches* to capture platform independent manufacturing economics but only stores 2.0-3.5 kg H_2 in 5 -10 ksi tanks (120-210 mi @ 60 mpg)

QuickTime™ and a TIFF (PackBits) decompressor are needed to see this picture.

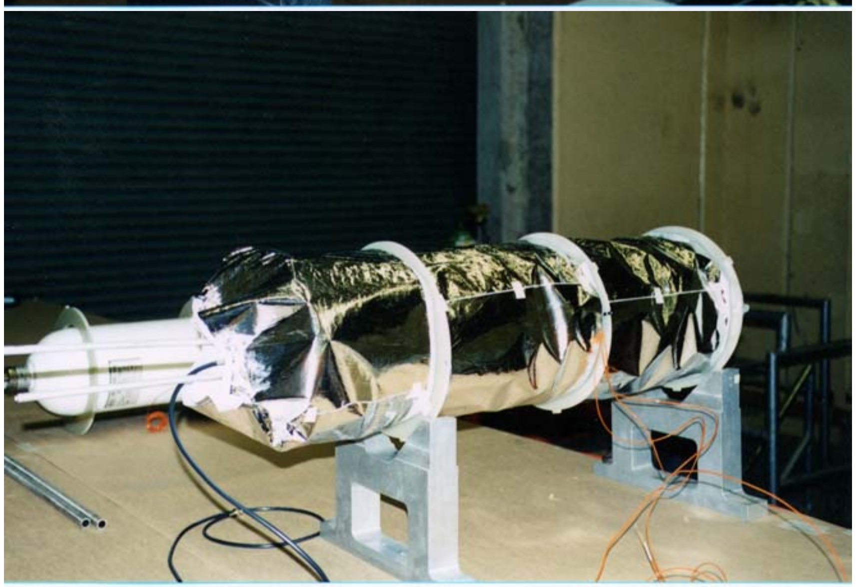
Nonlinear H_2 gas density vs. pressure is the fundamental property characteristic of gaseous H_2 limiting storage capacity to ~10 kg H_2 in 250 L (66 gal) vessels



Cooling from 300 K to 80 K or to LH_2 (20 K) reduces H_2 volume dramatically but energy intensity rises at cryogenic temperatures



Cryogenic compatible pressure vessels compromise between LH_2 (20 K) and high pressure H_2 (300 K) storage

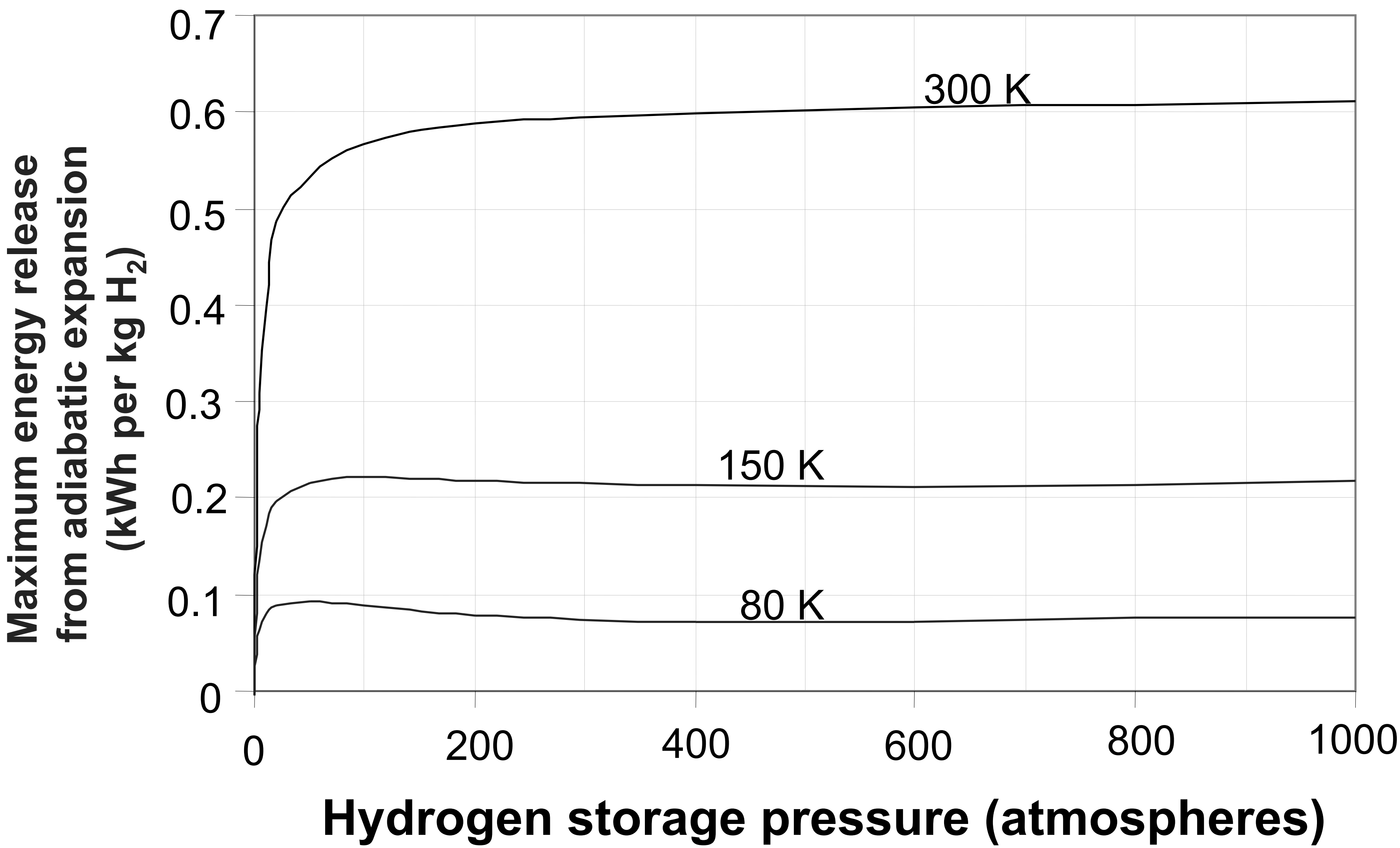
High pressure eliminates the H_2 boiloff of LH_2 (low-pressure) tanks

More *compact* and/or lower pressure than conventional (300 K) vessels

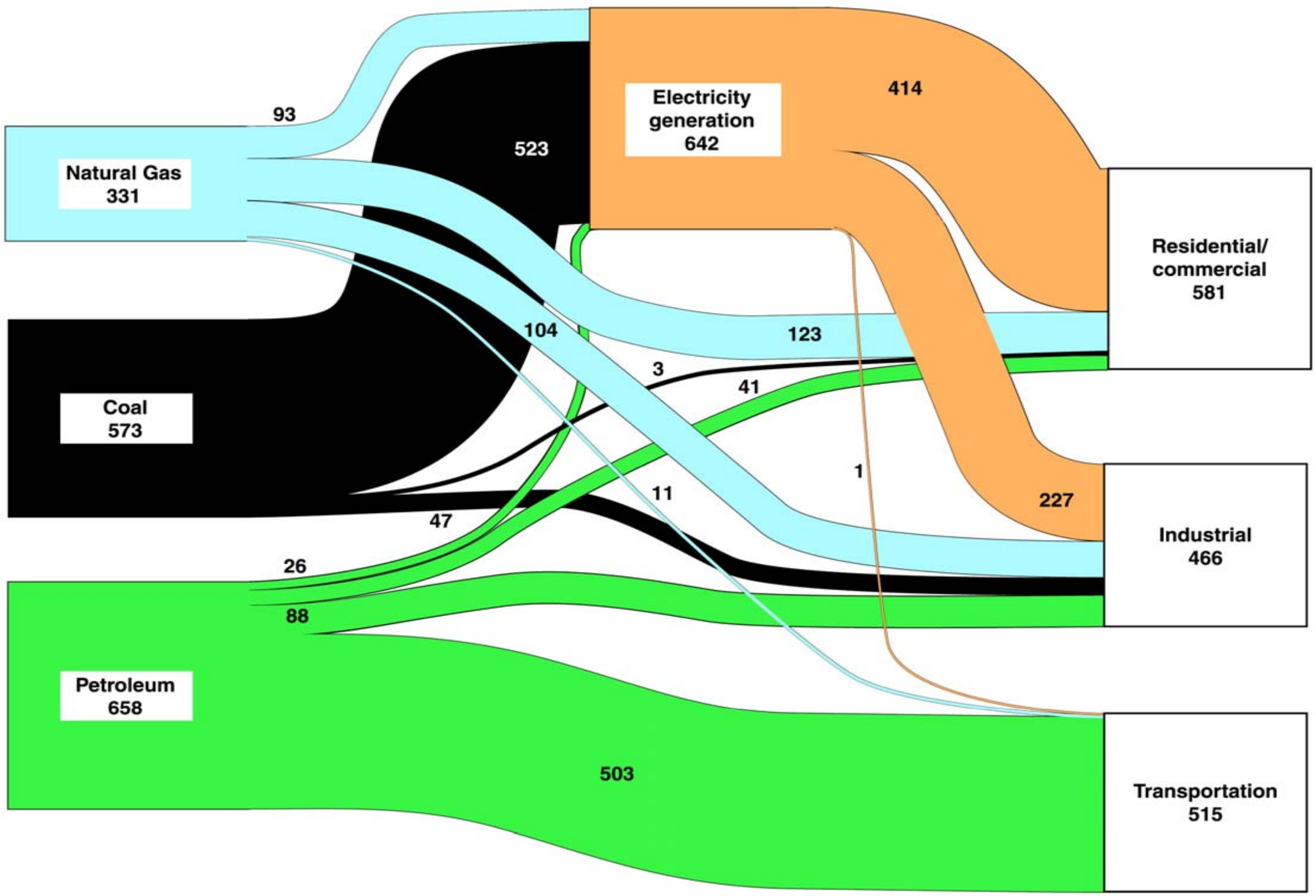
Can be refueled *flexibly*

300 K H_2 (urban)
or
Cryogenic (80 K) H_2 & LH_2 (highway)

The theoretical instantaneous maximum energy release from an H_2 vessel rupture is dramatically lower for cryogenic H_2 and *independent* of pressure above 20-100 atm



2000 U.S. carbon (dioxide) emissions from energy consumption—1547* MtC

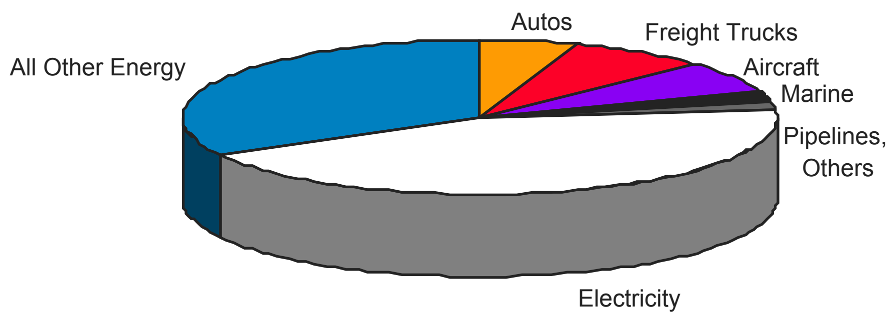


Source: Energy Information Administration
*Includes adjustments of 14 million metric tons of carbon from U.S. territories, less 28 MtC from bunker fuels

Lawrence Livermore National Laboratory, April 2002
http://en-env.llnl.gov/flow/

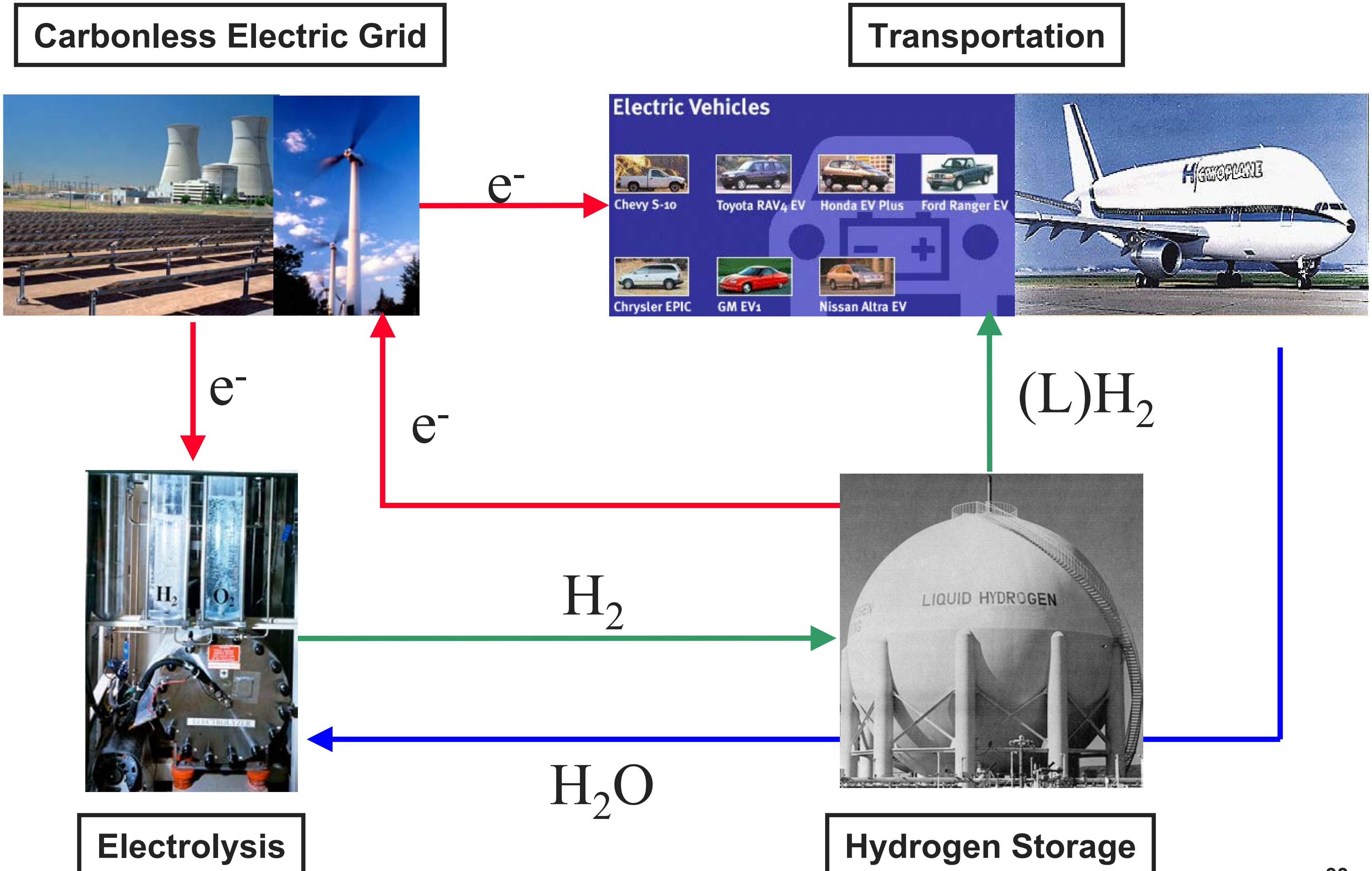
Future deep greenhouse gas cuts must come from electricity and transportation

Transportation (23%) and electricity (44%) will account for 2/3 of all US energy-related carbon emissions



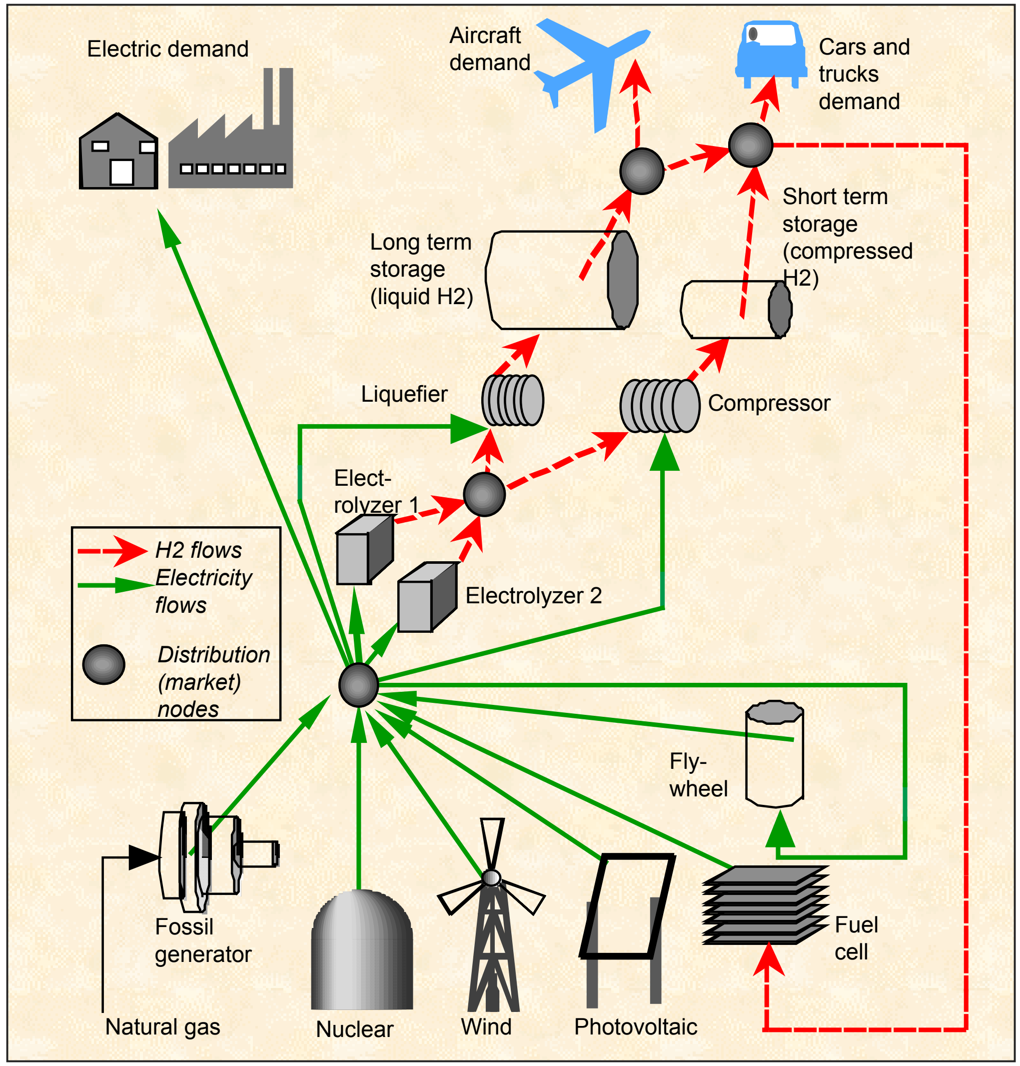
EIA 2020 projection, adjusted for full PNGV passenger vehicle implementation

Complete integration of non-fossil electricity with transportation will require H_2 use beyond automobiles

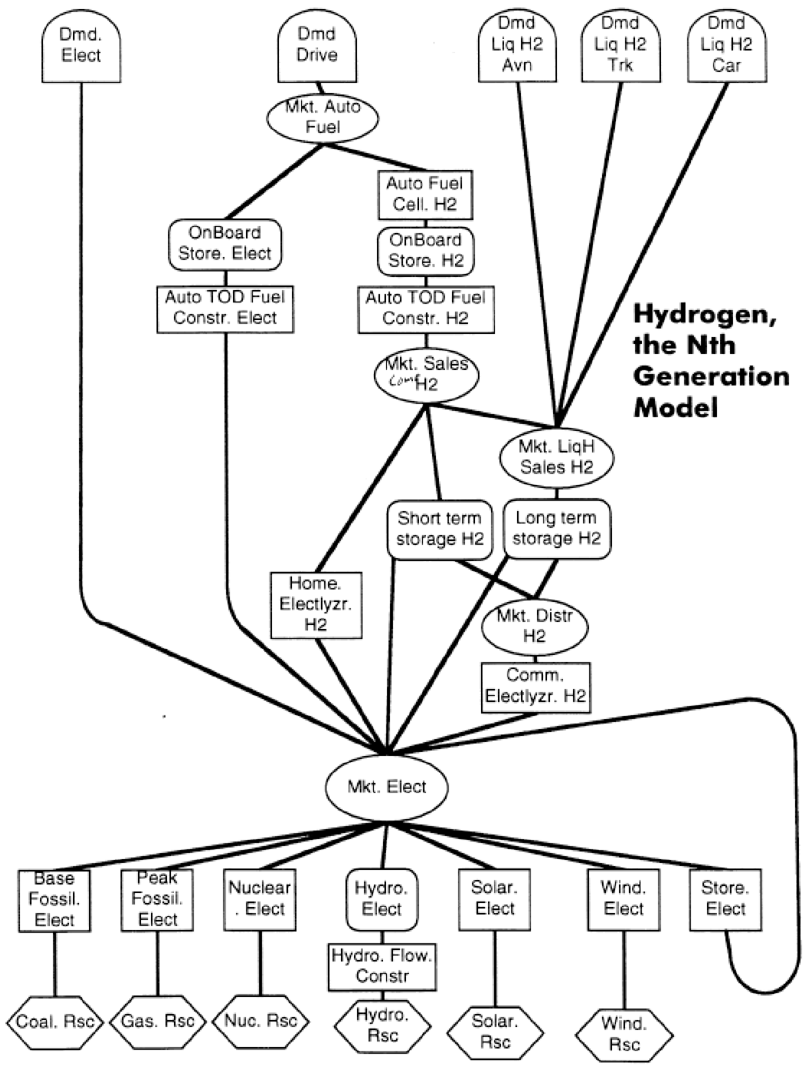


LLNL has constructed an equilibrium network model integrating hourly demand patterns with generation of hydrogen transportation fuel and electricity

- This system has
  - □120,000 inequality constraints
  - □25,000 equality constraints
- Nine capacities must be determined
- Each hour allocations must be made for
  - Five generators
  - Two electrolyzers
  - Withdrawals from long and short-term storage
  - Purchases of H2 by the storage devices



Carbonless electricity and H_2 transportation markets modeled using *simultaneous* equilibrium optimization



Hourly Electricity and Transportation Demands

Fuel Cell Vehicle Refueling Patterns

Short and Long Term Hydrogen Storage

Hourly Variations in Electrolytic Hydrogen Production

Electricity for both Grid use and Hydrogen Production

Hourly Electric Generation from a mix of Technologies

Solar, Wind, Hydro Resource Patterns and Availability

Hypothesis: Coupling carbonless electricity sources with hydrogen fuel production can reduce the cost of deep carbon reductions

Electricity Supply Variations

Large carbon reductions in the electric sector will require significant amounts of intermittent electricity sources (solar and wind)

Hydrogen Fuel: Flexible Load and Energy Storage

Electrolytic hydrogen production would be a very large and flexible load

Utility hydrogen storage could also serve as transportation fuel storage

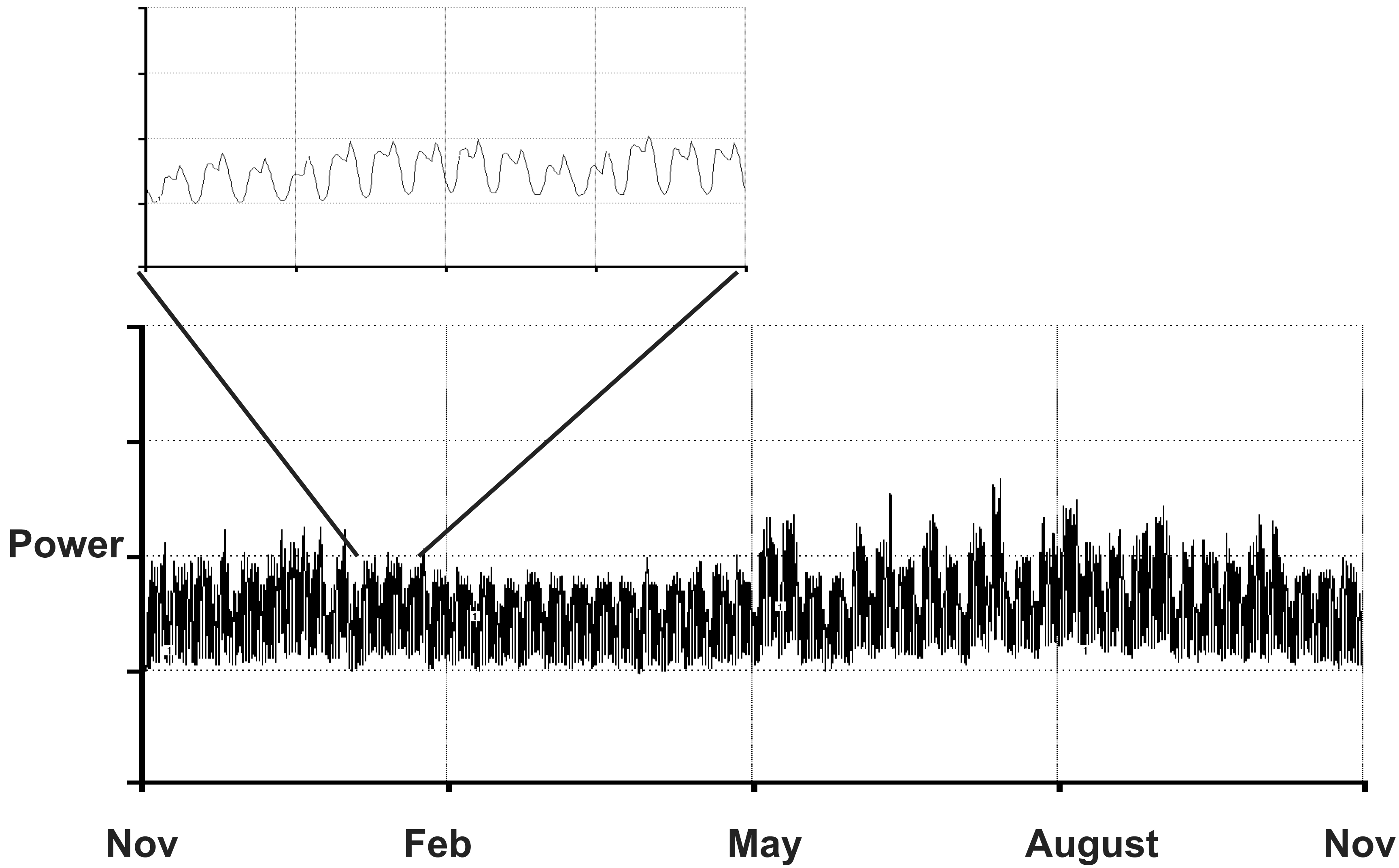
Shared Functions Reduce Overall Cost

Hydrogen and electric infrastructure would serve both electricity and transportation sectors

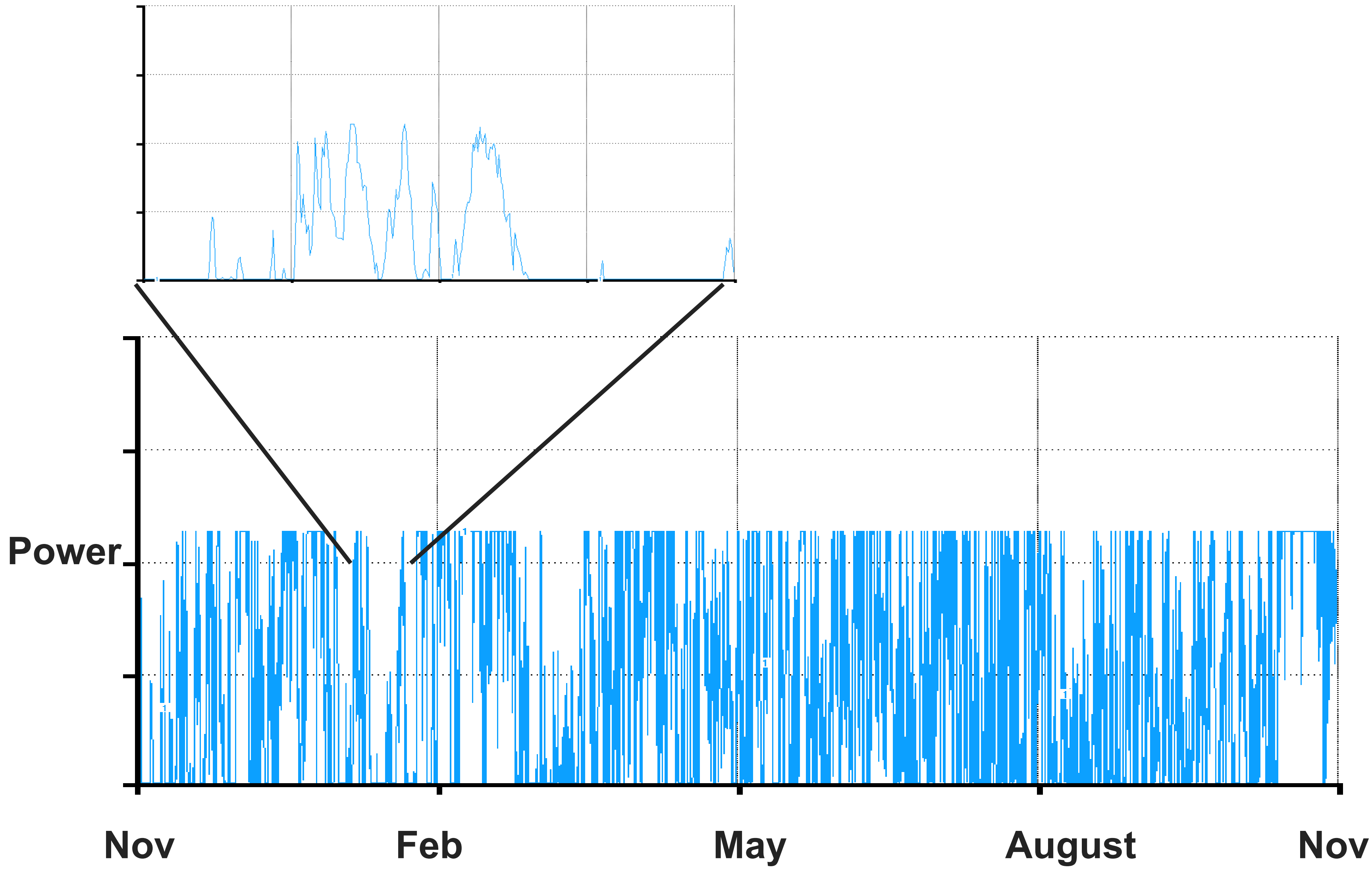
Decentralized production of electricity and hydrogen can ease transmission and distribution requirements

Carbonless Electricity and Transportation Would Eliminate 2/3 of US CO_2 Emissions

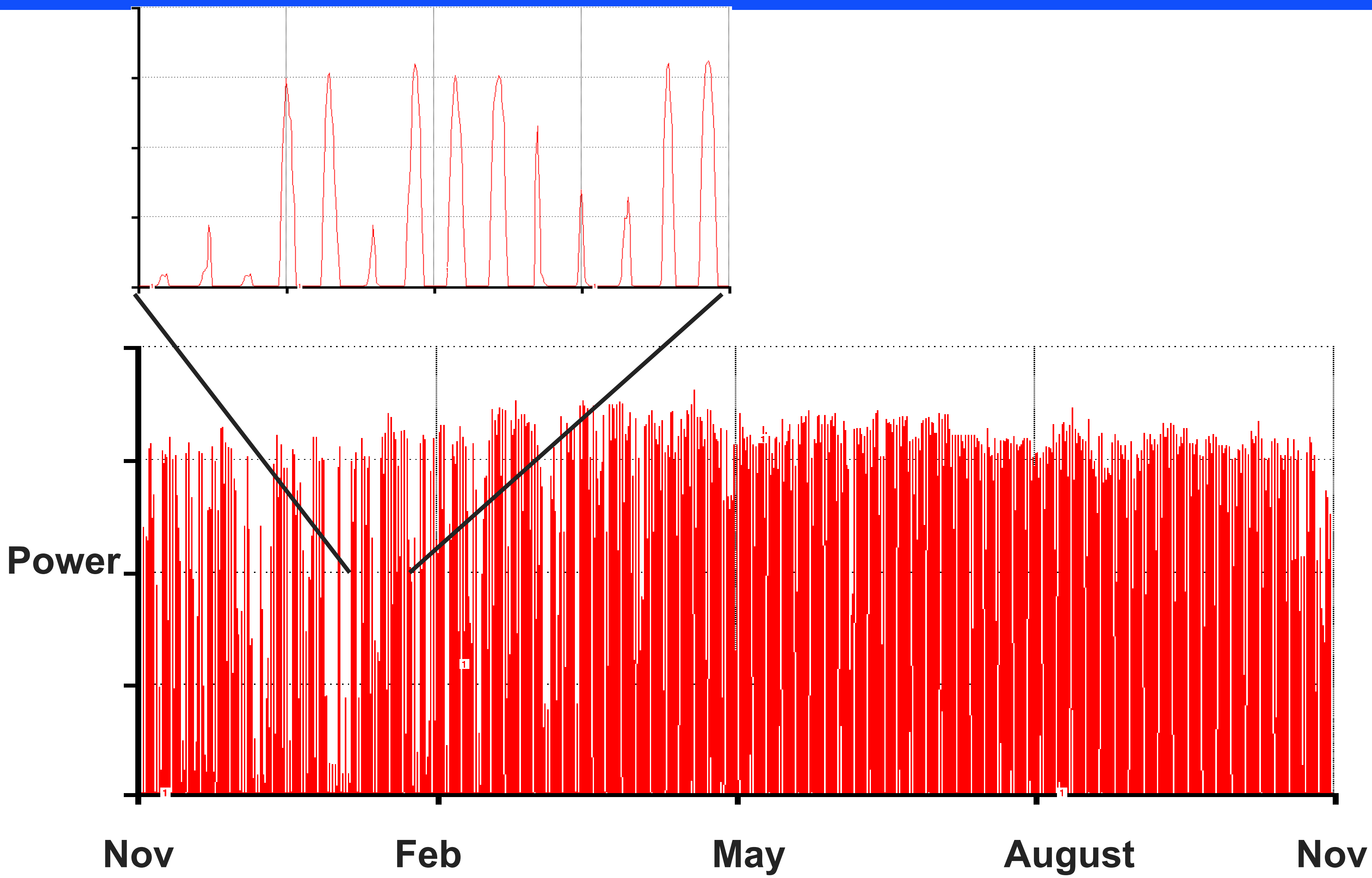
Typical electric demand variations exhibit clear hourly, daily, weekly, and seasonal patterns



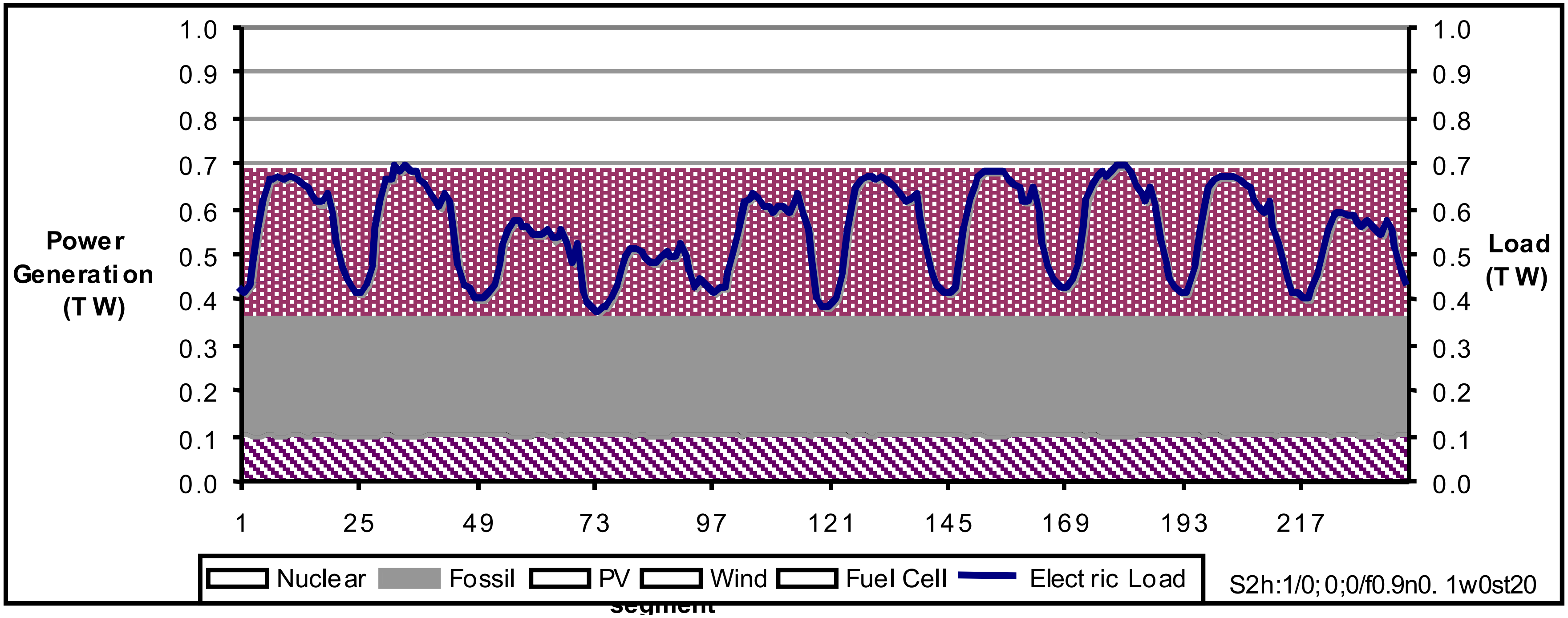
Wind energy supply patterns show great variability over daily, weekly and seasonal periods



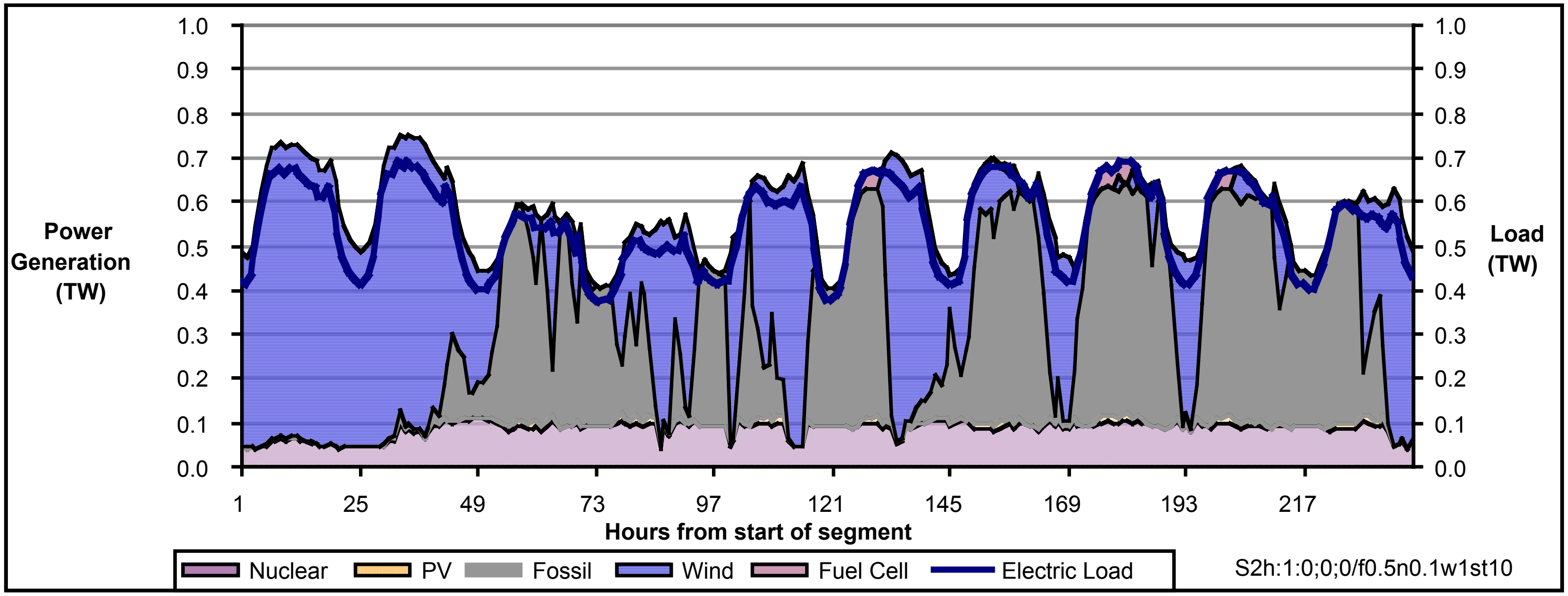
Typical solar supply patterns show marked seasonal variability, but predictable daily patterns



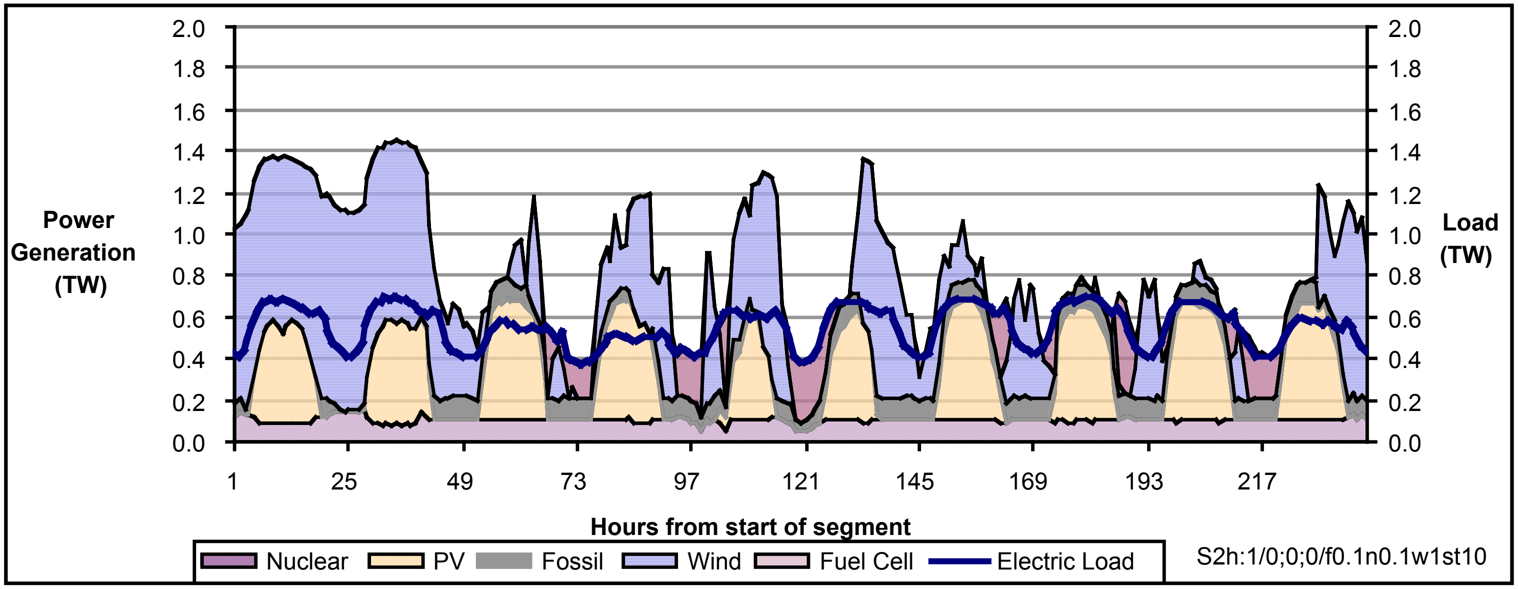
Modelling Electricity Production Patterns: Baseload Nuclear Balanced by Fossil Generation



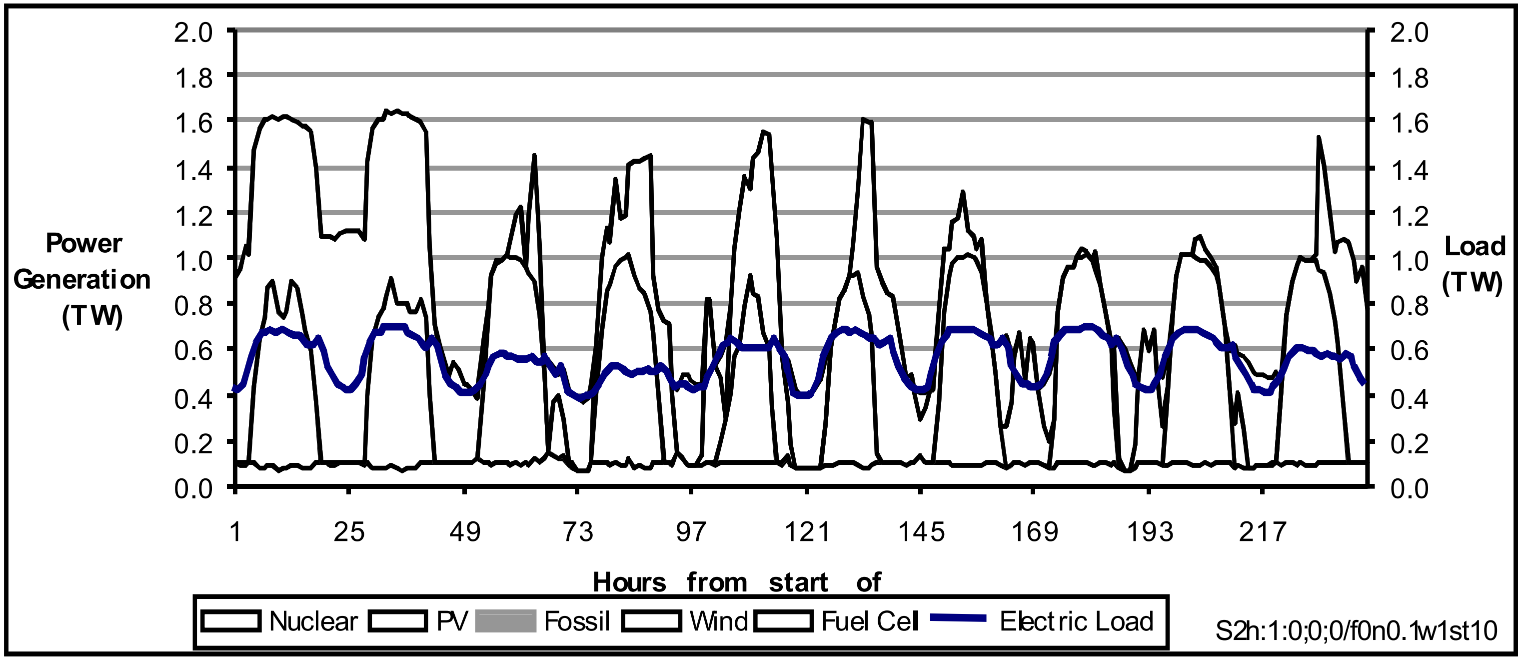
Modelling electricity production patterns: Baseload nuclear, wind/fossil hybrid



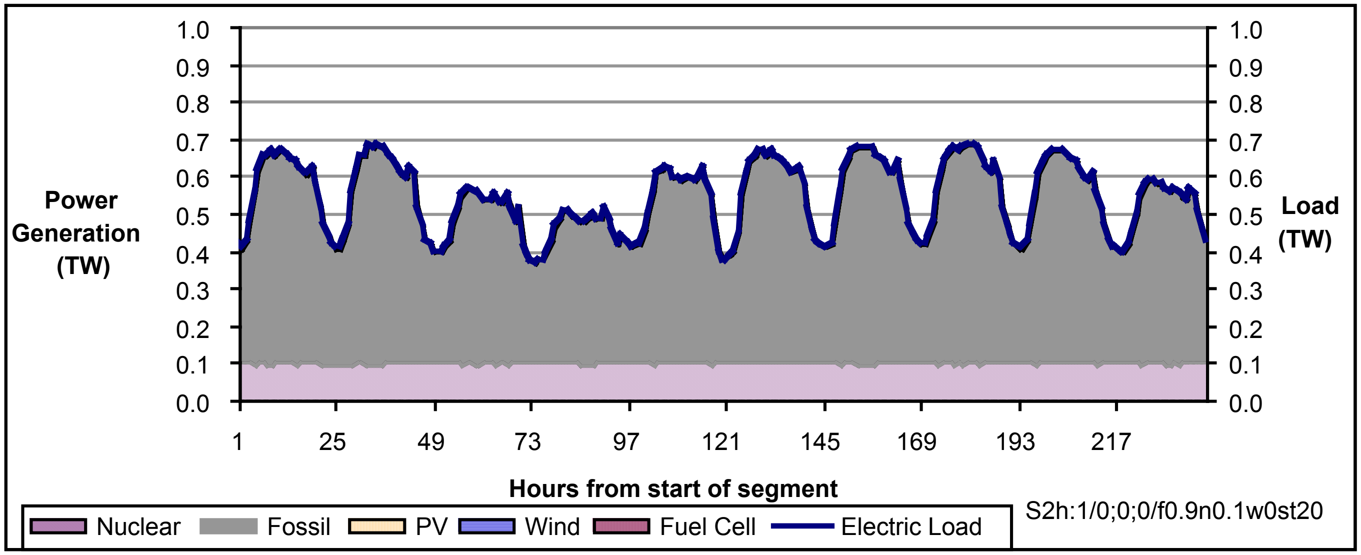
Modelling Electricity Production Patterns: Wind/Fossil/Solar



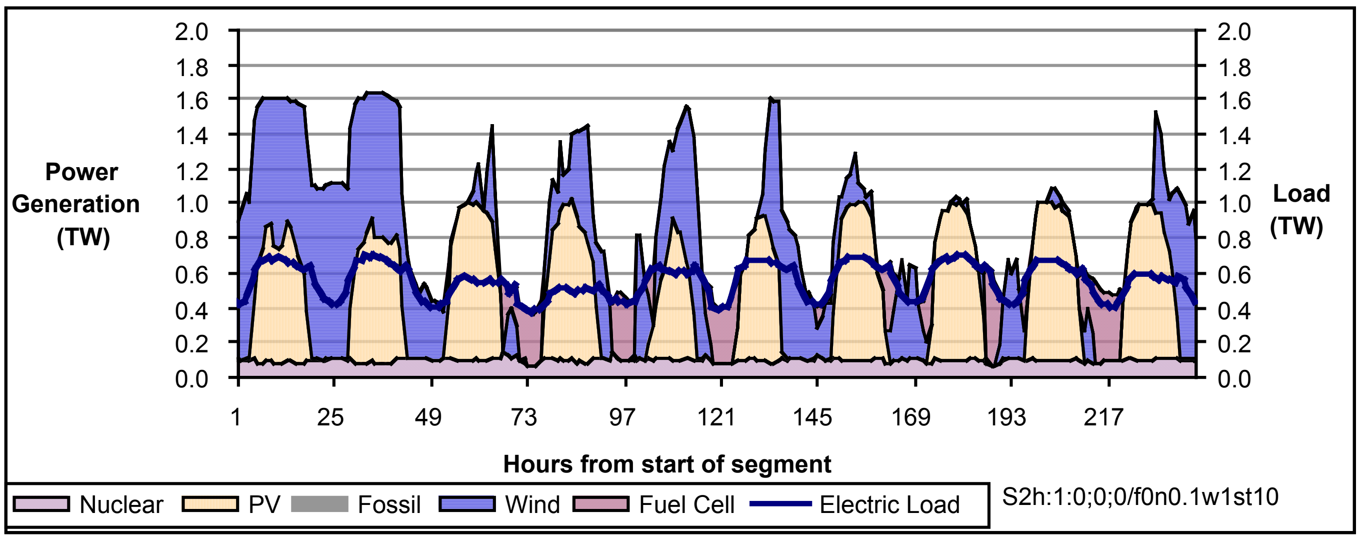
Modelling Electricity Production Patterns: Nuclear/Solar/Wind and H2 Fuel for cars



Projected patterns (10 days) of electricity demand supplied by fossil & non-fossil sources (with H_2 fuel produced from excess electricity)

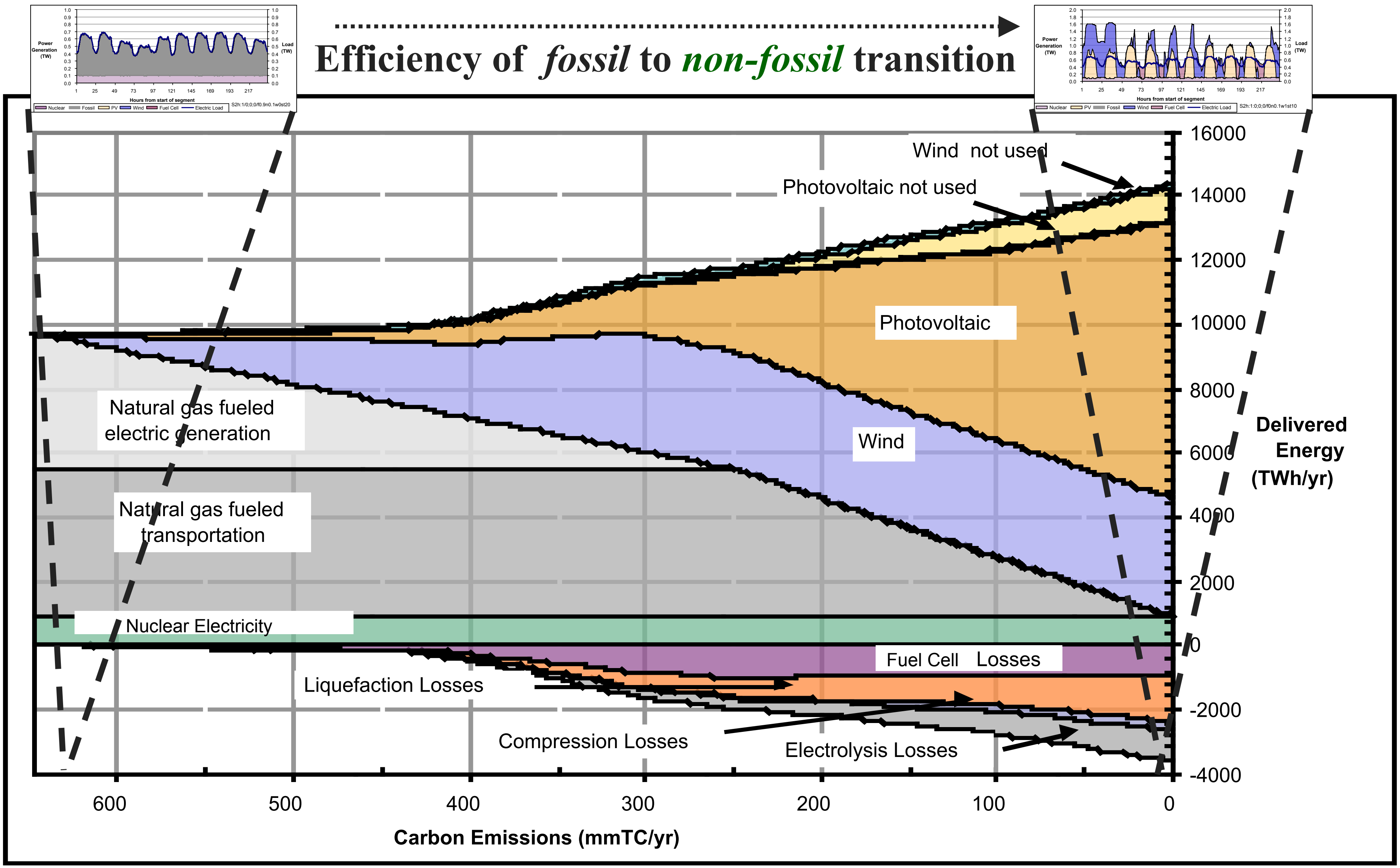


Natural Gas (CH_4)
&
Nuclear/Hydro

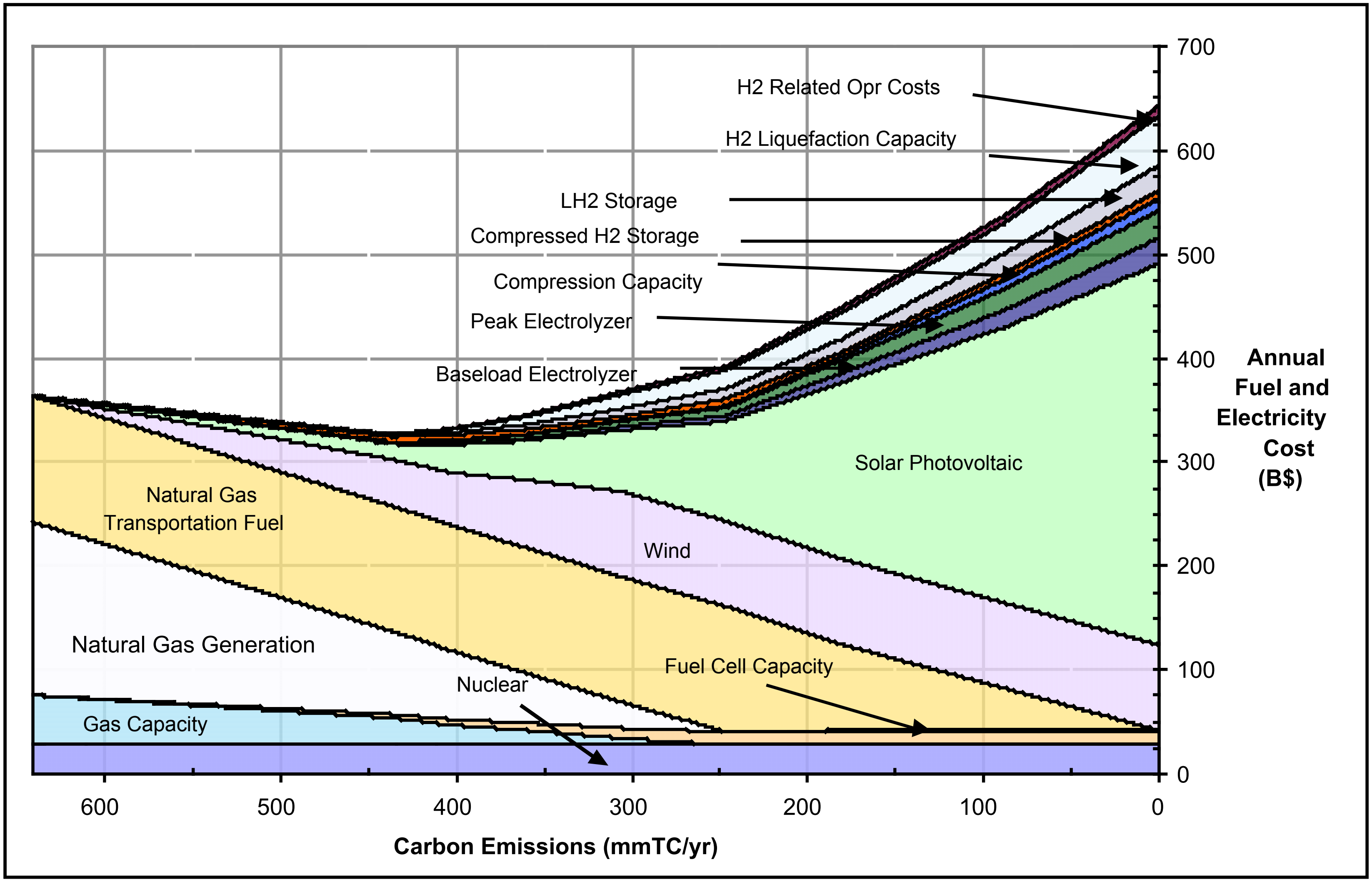


Solar
Wind
Nuclear/Hydro
H_2 electrolysis
Night-time fuel cell

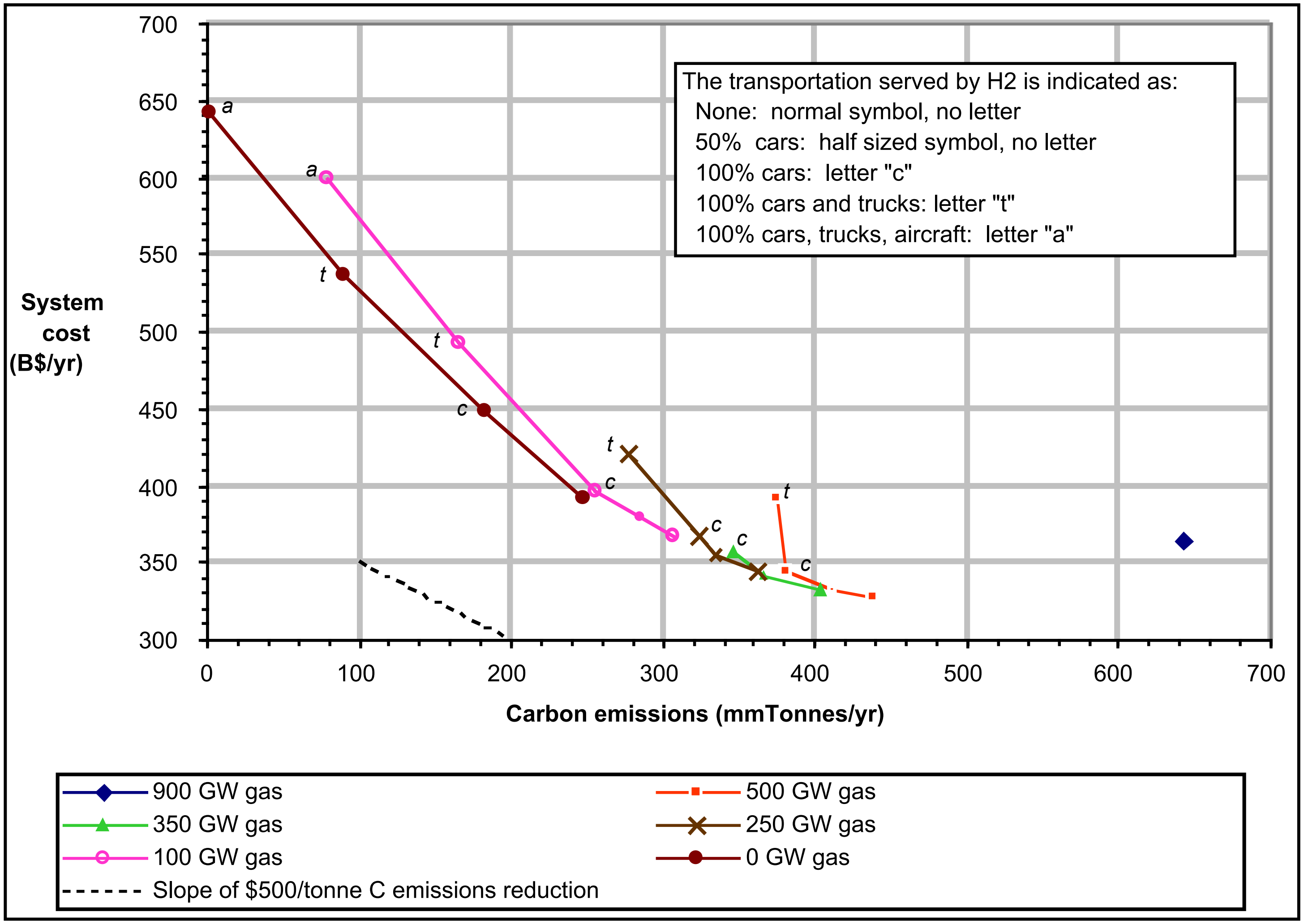
Carbonless electricity combined with H_2 transportation can replace CH_4 but could need 1/3 more energy for LH_2, electrolysis, and utility fuel cell operations



Efficiency will determine the economics of H_2 because the H_2 infrastructure (e.g. fuel cells) will cost less than the energy it carries



Cost and emissions for a variety of carbon reduction paths: timing of H2 vehicle intro appears flexible



Aggressive efficiency and economic assumptions were used (both for fossil and non-fossil)

		Capital Cost	Fuel/Power Cost	Efficiency
Electricity Sources	Gas Combined Cycle	$600/kW	1.9 c/kwh	56%
	Nuclear	$2000/kW	small	-
	Hydroelectric	$2000/kW	small	-
	Wind	$655/kW	small	-
	Solar Thermal (12hr)	$2500/kW	small	-
	Photovoltaic	$1100/kW	small	-
Hydrogen Infrastructure	Electrolysis(Steam)	$500/kW	small	92%
	Utility fuel cells	$200/kW	small	50%
	CH_2 storage	$6/kWh H_2	$100/kW	91%
	LH_2 storage	$.30/kWh LH_2	$500/kW	75%

Hydrogen Vehicles

~80 mpg hydrogen passenger vehicles ($500 extra) with 400-mile range

EIA efficiencies for trucks. LH_2 aircraft were EIA x 1.1

Note: 4% Real Discount Rate, 20 -30 yr life for capital equipment. Conventional electricity costs drawn from EPRI, GRI, EIAI. Hydrogenand renewable electricity costs from DOE *rnewable energy characterizations(1998)*
..

Technological prerequisites for widespread implementation of H_2 as an energy carrier

- Energy efficient design, integration, *and* operation of H_2 and electricity infrastructure
  ("just in time" liquefaction, flexibly fueled hydrogen onboard storage)
- 25-40 km/L or 60-100 mpg H_2 (fuel-cell) light-duty vehicles
- Efficient (80-90%) electrochemistry for both forward & reverse reactions (H_2 fuel cells *and* H_2O electrolysis)
- Non-fossil electricity @ $0.05-0.07/kWh

Potential improvements to be examined

- Electrolysis and fuel cells close-coupled for heat and O_2 integration where needed.
- "Peak" and "Baseload" electrolyzers and Fuel Cells
- Potential synergies with hydrogen for chemical industry (NH_3)
- Biomass and Natural gas for seasonal leveling, with minimal carbon sequestration burden

1.5 TW (13 Trillion kWh/yr) U.S. *circa* 2050 Carbonless Electricity and Transportation Scenario shows decarbonize the grid first

		Capacity (TW)	Capacity Factor	Trillion kWh/yr
Electricity Sources	Nuclear	0.1	0.9	0.8
	Hydroelectric	0.1	0.9	0.8
	Wind	1.0	.44	4.4
	Photovoltaic	3	.3	7.0
				13 total
		Miles/year	kg H_2/yr	
H_2 Transportation	400 million autos (100 mpg)	15k	60 billion	2.0 (3.2)
	2 million trucks (15 mpg)	150k	20 billion	0.66 (1.1)
	400 million flights (60 seat mpg)	6k	40 billion (LH_2)	1.33 (2.7)
			120 billion	4 (7) total
Direct Electricity use	400 million people @ 15000 kWh/yr per person			6

CO_2 Displaced

6 trillion kWh of displaced coal generation (66% efficient) is 1 GtC

or 6 trillion kWh of displaced natural gas generation (66% Efficient) is 0.5 GtC

7 trillion kWh of electricity creates 4 trillion kWh of H_2 offsetting only 0.25 GtC of oil

Only 30 years of economic/technological change have altered the H_2 “economy” concept dramatically
How robust are our conceptions for the next 100 years?

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The Hydrogen Economy

A case is made for an energy regime in which all energy sources would be used to produce hydrogen, which could then be distributed as a nonpolluting multipurpose fuel

by Derek P. Gregory

The basic dilemma represented by what has been termed the "world energy crisis" can be simply stated: At the very time that the world economy in general and the economies of the industrialized countries in particular are becoming increasingly dependent on the consumption of energy, there is a growing realization that the main sources of this energy—the earth's nonrenewable fossil-fuel reserves—will inevitably be exhausted, and that in any event the natural environment of the earth cannot readily assimilate the by-products of fossil-fuel consumption at much higher rates than it does at present without suffering unacceptable levels of pollution.

What is not generally recognized is that the eventual solution of the energy problem depends not only on developing alternative sources of energy but also on devising new methods of energy conversion. There is, after all, plenty of "raw" energy around, but either it is not in a form convenient for immediate use or it is not in a location close enough to where it is needed. Most of the research-and-development effort in progress in the U.S. on the energy problem is devoted to finding ways to convert chemical energy (derived from fossil fuels), nuclear energy (derived from fission or fusion reactions) and solar energy (derived directly from the sun) into electrical energy.

At present nuclear-fission plants supply about 1.6 percent of the electricity consumed in the U.S. (Of the remainder, fossil-fuel plants supply about 82 percent and hydroelectric plants about 16 percent.) Assuming that the development of economically feasible "breeder" reactors will soon eliminate any short-term concern about the resource limitation of nuclear energy, then by the year 2000 nuclear plants may be supplying as much as half of the nation's electricity.

If this projection is correct, and if the "energy gap" of the future is to be filled with nuclear power made available to the consumer in the form of electricity, then the U.S. will have gone a long way toward becoming an "all-electric economy." This trend can be detected already: the demand for electricity is currently growing in the U.S. at a much higher rate than the overall energy demand [*see illustration on next page*]. It has been estimated that whereas the overall U.S. energy consumption will double by the year 2000, the demand for electricity will increase about eightfold, raising the electrical share of total energy consumption from about 10 percent to more than 40 percent.

The question naturally arises: How desirable is this trend toward a predominantly electrical economy? Specifically, are there any other forms of energy that can be delivered to the point of use more cheaply and less obtrusively than electrical energy can? Consider such major energy-consumption categories as transportation, space heating and heavy industrial processes, all of which are primarily supplied today with fossil-fuel energy, mainly for reasons of economy and portability. As the fossil fuels run out, they will become more expensive, making the direct use of nuclear electrical energy relatively more economical. In this situation a case can be made for utilizing the nuclear-energy sources indirectly to produce a synthetic secondary fuel that would be delivered more cheaply and would be easier to use than electricity in many large-scale applications. In this article I shall discuss the merits of what I consider to be the leading candidate for such a secondary fuel: hydrogen gas.

In many respects hydrogen is the ideal fuel. Although it is not a "natural" fuel, it can be readily synthesized from coal, oil or natural gas. More important, it can be produced simply by splitting molecules of water with an input of electrical energy derived from an energy source such as a nuclear reactor. Perhaps the greatest advantage of hydrogen fuel, however, at least from an environmental standpoint, is the fact that when hydrogen burns, its only combustion product is water! None of the traditional fossil-fuel pollutants—carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrocarbons, particulates, photochemical oxidants and so on—can be produced in a hydrogen flame, and the small amount of nitrogen oxide (NO) that is formed from the air entering the

H_2 pipelines (large) were cheaper than power lines

Electric growth was thought to be 8x by 2000 (2x actual)

H_2 mostly for stationary uses
Automotive viewed as possible

not *mentioned* -
energy security
greenhouse gases
photovoltaics
wind
compressed H_2 on cars

Electricity was \$0.02/kWh
Gas was \$0.50/GJ

The H_2 transition will take 30-50 years, but is the essential element pivotal to *universal* and *enduring* solution of global challenges

- Clean Air, Water, Transportation
- Energy and Economic Security
- Stabilizing Greenhouse Gases
- Sustainable Development