

# Plug-in Hybrid Electric Vehicle (PHEV) Research Project

Presented to

Association of Professional Engineers & Geoscientists  
of Manitoba (APEGM)

February 15, 2008

by

Ed Innes, BScEE, MSc(EE)

**Emerging Energy Systems**

# What is a PHEV?

## Modified Prius' can save more money

Some Toyota Prius owners are modifying their cars with extra batteries to boost fuel efficiency. The batteries, which cost as little as a quarter to charge, allow the electric motor to power the car longer, reducing the gas used.

**Extra batteries** added for more electrical charge

**Generator**

**Gas engine**

**Electric motor**

**Battery**

**Gas tank**

**Power cord**  
connected to an outlet for extra electricity

Unmodified 60 mpg

Modified as much as 250 mpg

- **P**lug-in  
**H**ybrid  
**E**lectric  
**V**ehicle

- 120/240V Charging.

- Battery ranges:
  - HEV
  - PHEV-20
  - PHEV-30
  - PHEV-60
  - BEV

- Bio-fuel?

 **Manitoba Hydro**

[www.125mpg.com](http://www.125mpg.com)



*"It runs on its conventional gasoline-powered engine until it senses guilt, at which point it switches over to battery power."*

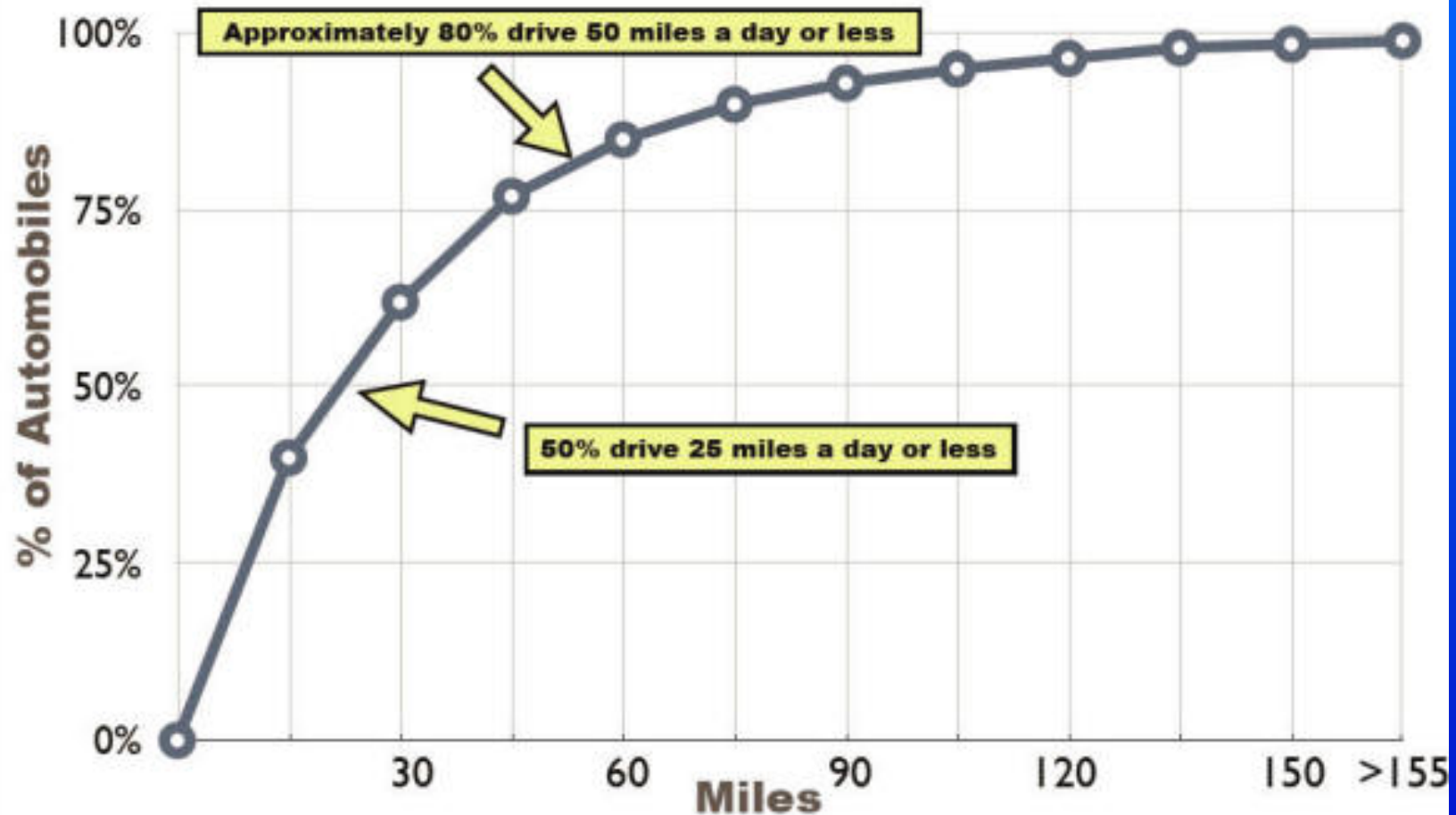
# PHEV Research Project

- Approved June 29, 2005.
- Purchased 2005 Toyota Prius Hybrid.
- Modify for plug-in capability:
  - 30 mile net electric range, 50 mile gas-electric range.
- Operate and collect data for one year.
- Goals:
  - Operation and reliability.
  - Cold weather capability.
  - Effects of PHEVs on the MH system.
  - Feasibility of off-peak charging.
  - Promote technology and increase public awareness.
- Converted in Monrovia, Calif. August 14, 2006.
- Re-converted at PHEV2007, Wpg. November 2, 2007.
- 2<sup>nd</sup> conversion: U of M, April 10, 2007.



# PHEV Gasoline Savings

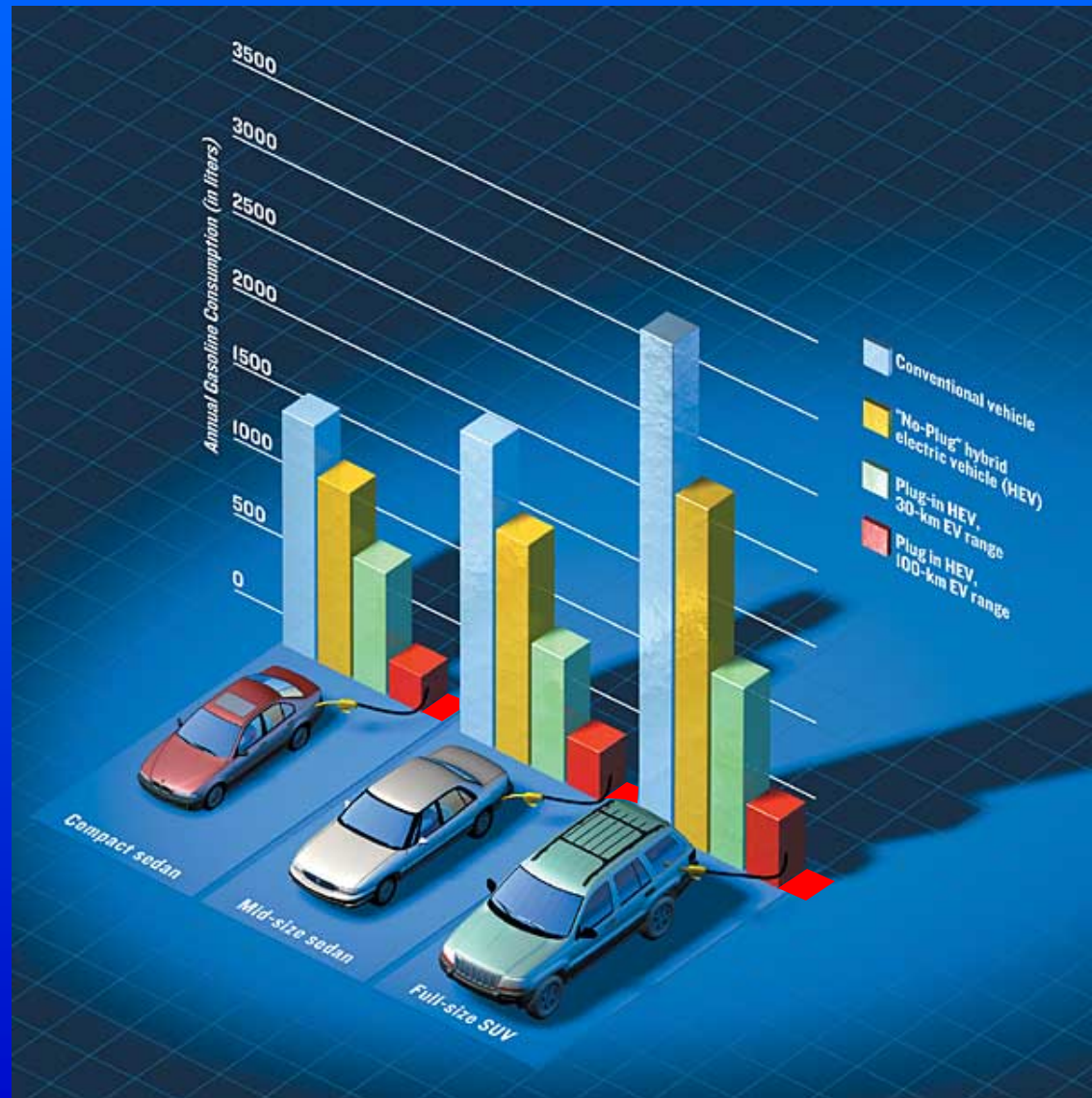
## Personal Vehicle Miles Driven Daily



Source: U.S. Department of Transportation, Federal Highway Administration, 1990 Nationwide Personal Transportation Survey (NPTS), Volpe National Transportation Systems Center, Cambridge, MA, 1999 | Nationwide Personal Transportation Survey 1990

# The Gasoline to Battery Continuum

- Hybrids save gasoline, but...
- Plug-in hybrids with only 20 mile electric vehicle range save more.
- 60 mile range saves a lot more.
- Battery electric vehicles save the most! (annual gasoline consumption = 0)

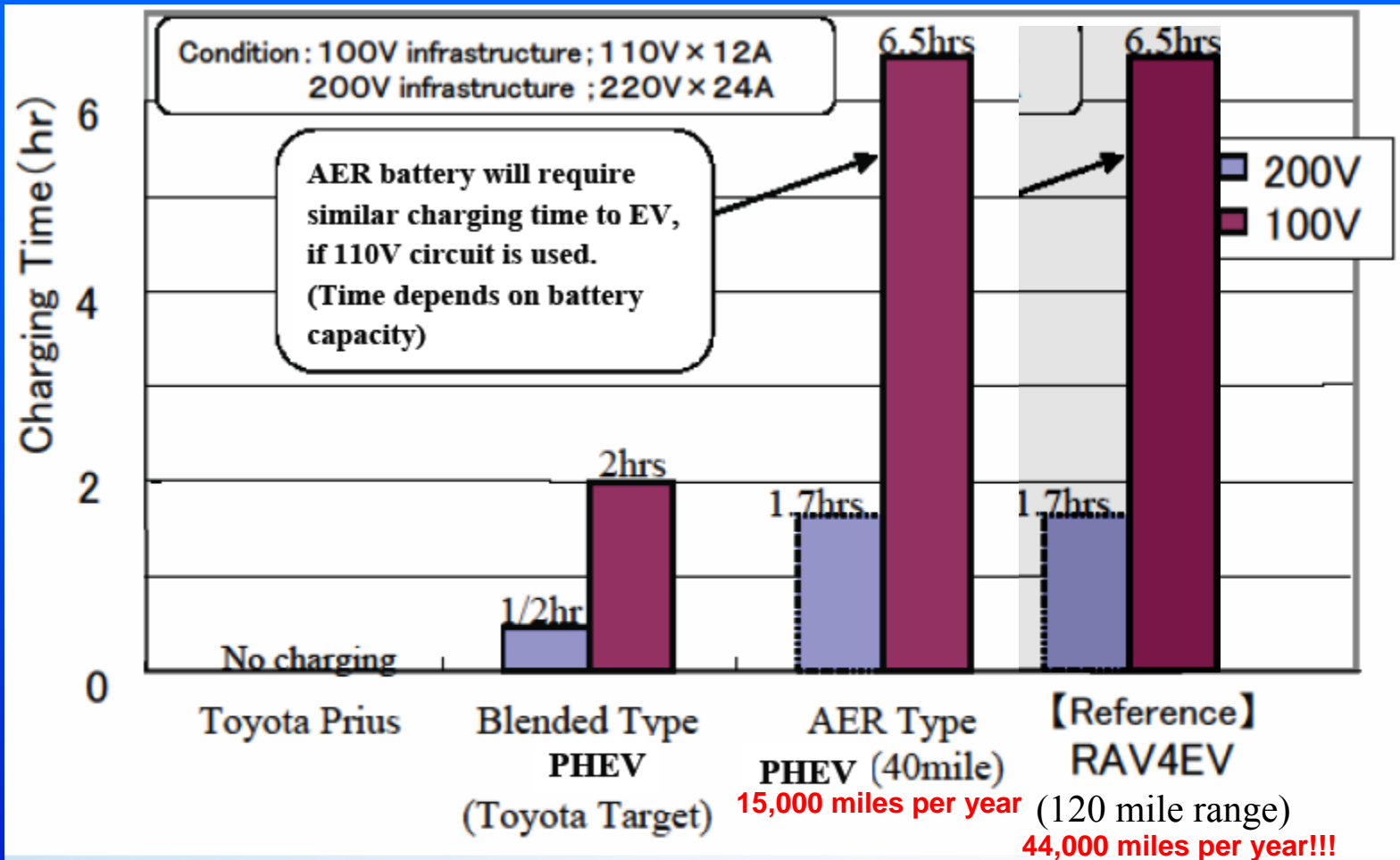


# Is it a BEV or a PHEV?



- BEV with optional gasoline generator trailer.
- When is a BEV a PHEV?
- Range not really an issue with EVs.

# Charging Time Error

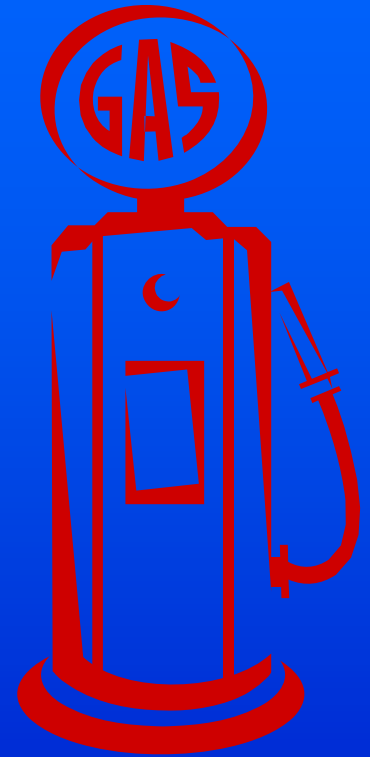


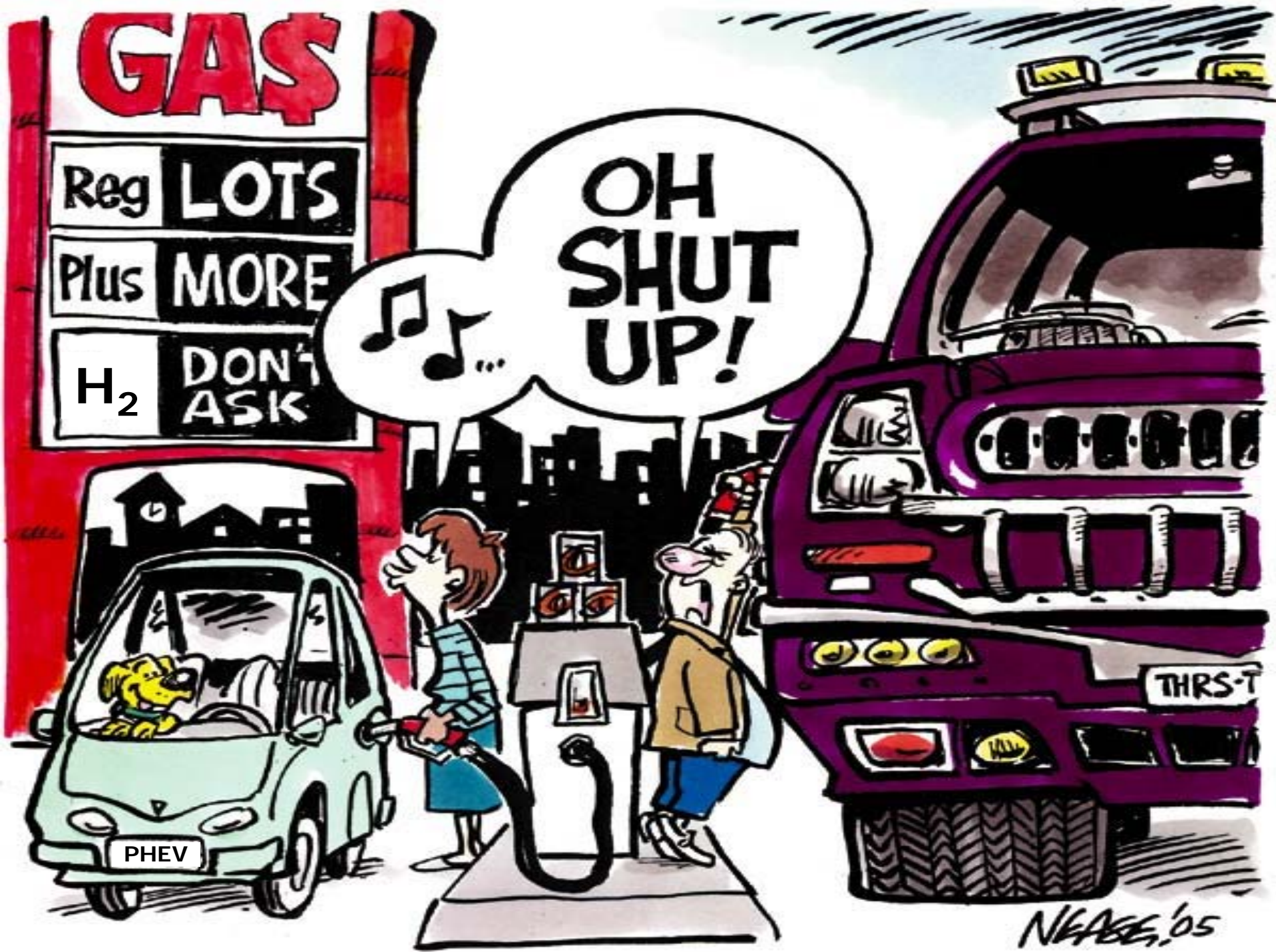
AER PHEV battery requires same charging time as EV !

**Charging time is limited by the amount of driving.  
It is not solely dictated by the size of the battery!**

# PHEVs Are Convenient

- Consider the time spent buying gasoline:
  - Assume for ordinary car:
    - 15 minutes per fill-up (5 driving, 5 filling, 5 paying).
    - 52 fill-ups per year (1 per week).
    - $15 \times 52 = 780$  minutes or 13 hours per year!
  - Assume for PHEV:
    - 5 fill-ups per year.
    - $15 \times 5 = 75$  minutes or 1¼ hours per year.
  - *You save almost 12 hours a year!!*
- A pure BEV with very rapid charge batteries would have a similar time saving with:
  - Regular slow charging at home.
  - Occasional fast charging at an “electric gas” station.





# Why Alternative Transportation?



## Global Warming

It just ain't cool.

DIMMING  
the  
SUN

New evidence that air pollution has masked the full impact of global warming suggests the world may soon face a heightened climate crisis.



## Pollution

6,000 dead in  
Ontario!



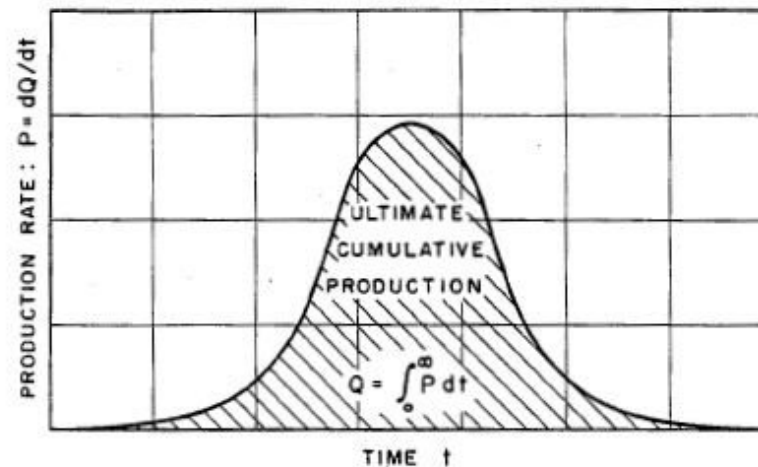
# Energy Security



- 1973 energy crisis.
- 55 mph US nationwide.
- 18% fuel saving.
- Widespread public resistance despite gas shortages and lineups.

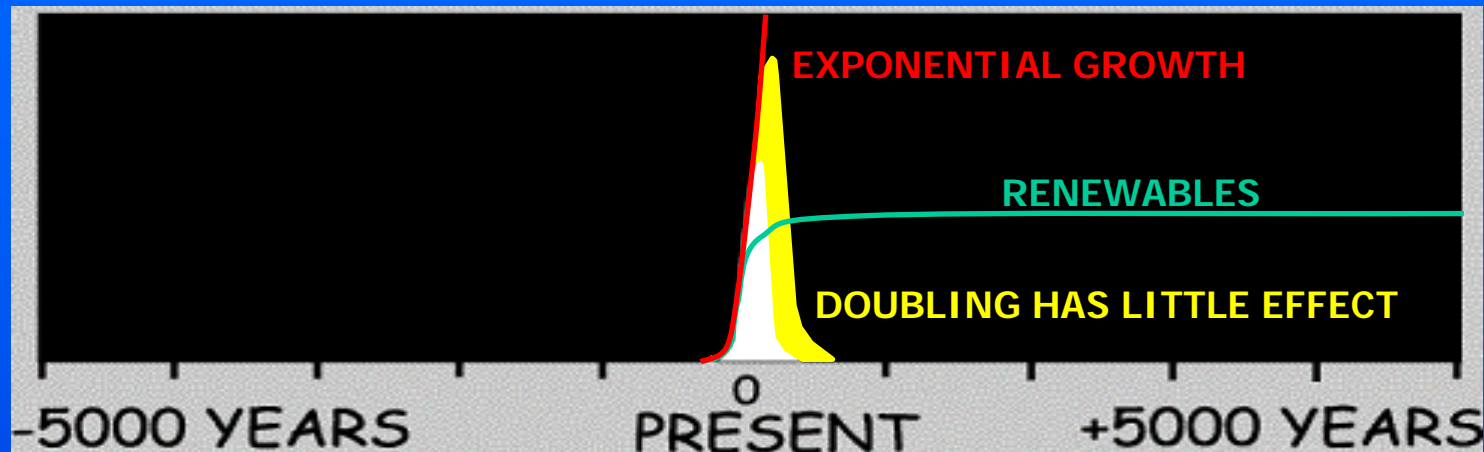


# M. King Hubbert (1903-1989)



- Hubbert published a mathematical model of resource consumption in 1949.
- In 1956, he correctly predicted that “US 48” oil would peak about 1970 and permanently decline thereafter.
- He predicted the world would peak after 2000.

# The Long Term Hubbert View

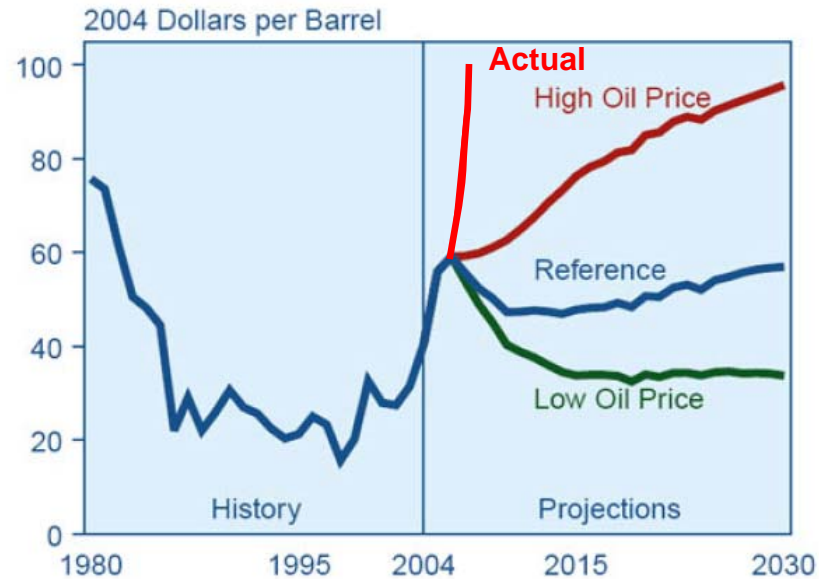


- “The consumption of energy from fossil fuels is thus seen to be but a ‘pip,’ rising sharply from zero to a maximum, and almost as sharply declining, and thus representing but a moment in the total of human history.”

- M. King Hubbert, 1949

# Price of Oil.....Oops!

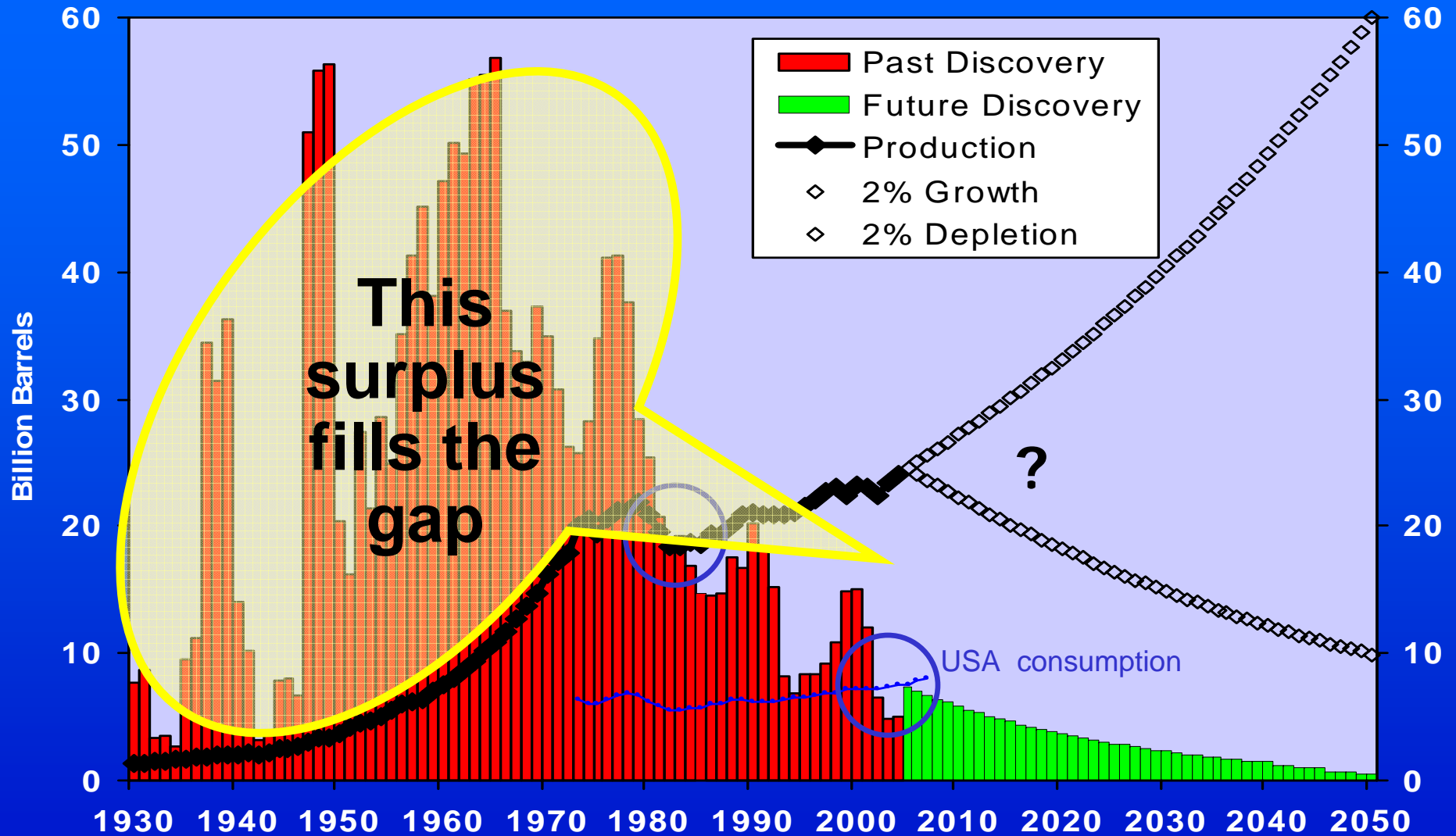
Figure 32. World Oil Prices in Three Cases, 1980-2030



Sources: **History:** Energy Information Administration (EIA), *Annual Energy Review 2004*, DOE/EIA-0384(2004) (Washington, DC, August 2005), web site [www.eia.doe.gov/emeu/aer/](http://www.eia.doe.gov/emeu/aer/).  
**Projections:** EIA, *Annual Energy Outlook 2006*, DOE/EIA-0383(2006) (Washington, DC, February 2006).

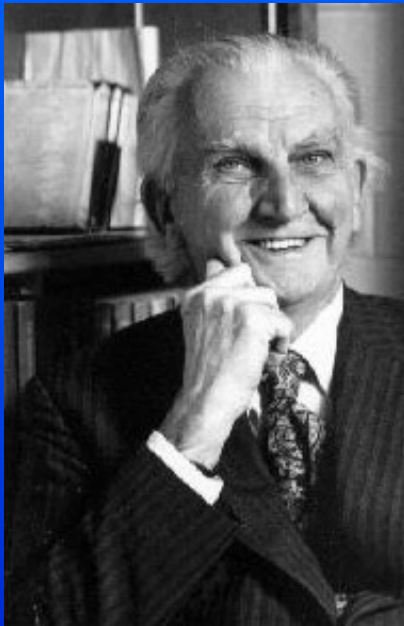
- Predicting the future is risky business.
- Even the best estimates can be dead wrong.

# Oil Discovery vs Production Trends



- Rapidly increasing demand for a declining fossil resource?

# Definition of a Madman



“Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist.”

Kenneth E. Boulding 1910-1993

# Not Just Energy Security



- Fossil “fuels” are also key ingredients in asphalt, tires, insulation, food, medicine, pesticides, as well as numerous other chemical products.
- Alternative energy is *not* a substitute!

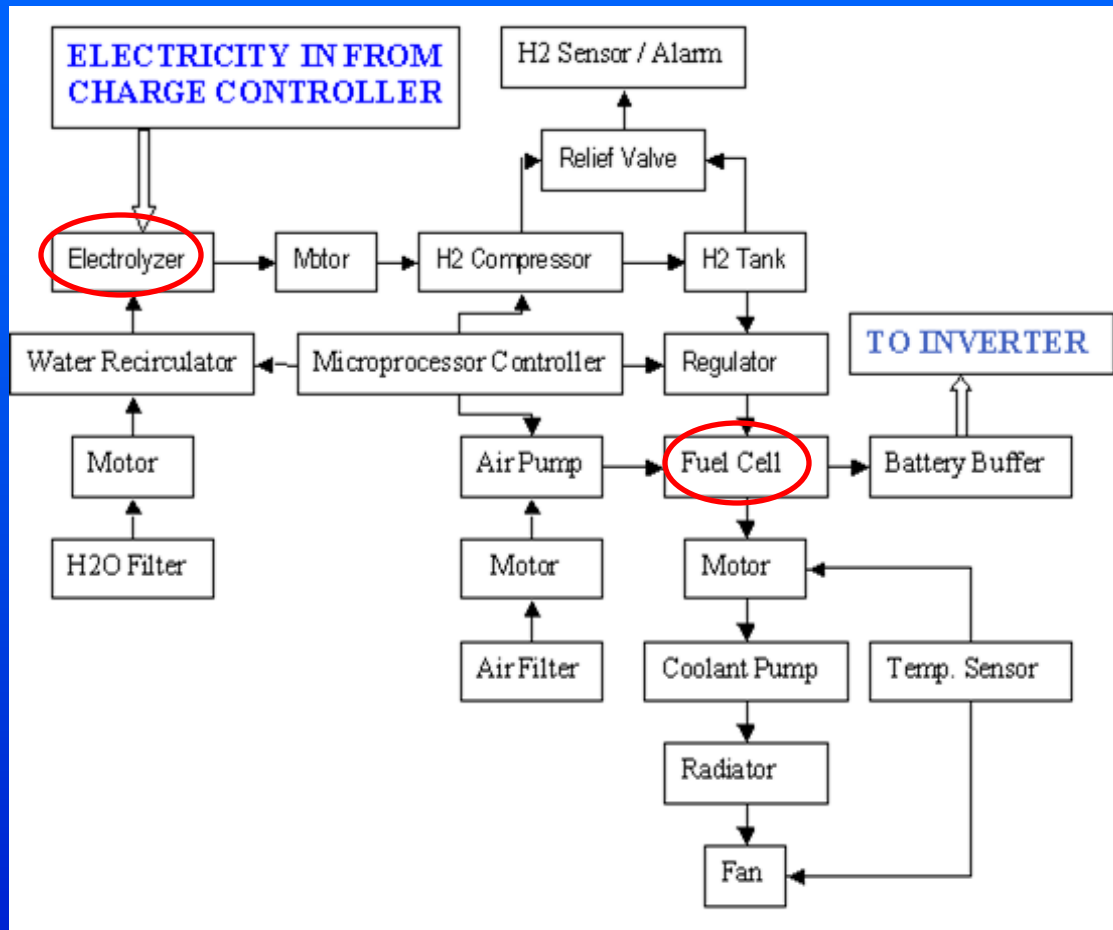
# What About Hydrogen?

- Isn't hydrogen the *fuel of the future*, the efficient clean wonder fuel, that will solve all our problems?
- Hydrogen is an *energy parasite*, not a fuel source.
- Hydrogen *consumes* a lot of energy:
  - when created
  - when handled
  - when used.
- Hydrogen is *rarely clean*:
  - comes primarily from natural gas and coal
  - used primarily by the petrochemical industry.

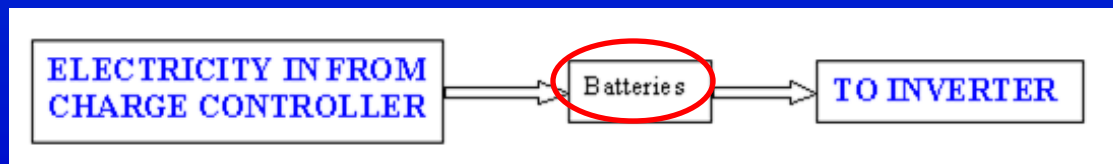
Hydrogen production from natural gas, liquid gas, naphtha, residual oil, and coal.



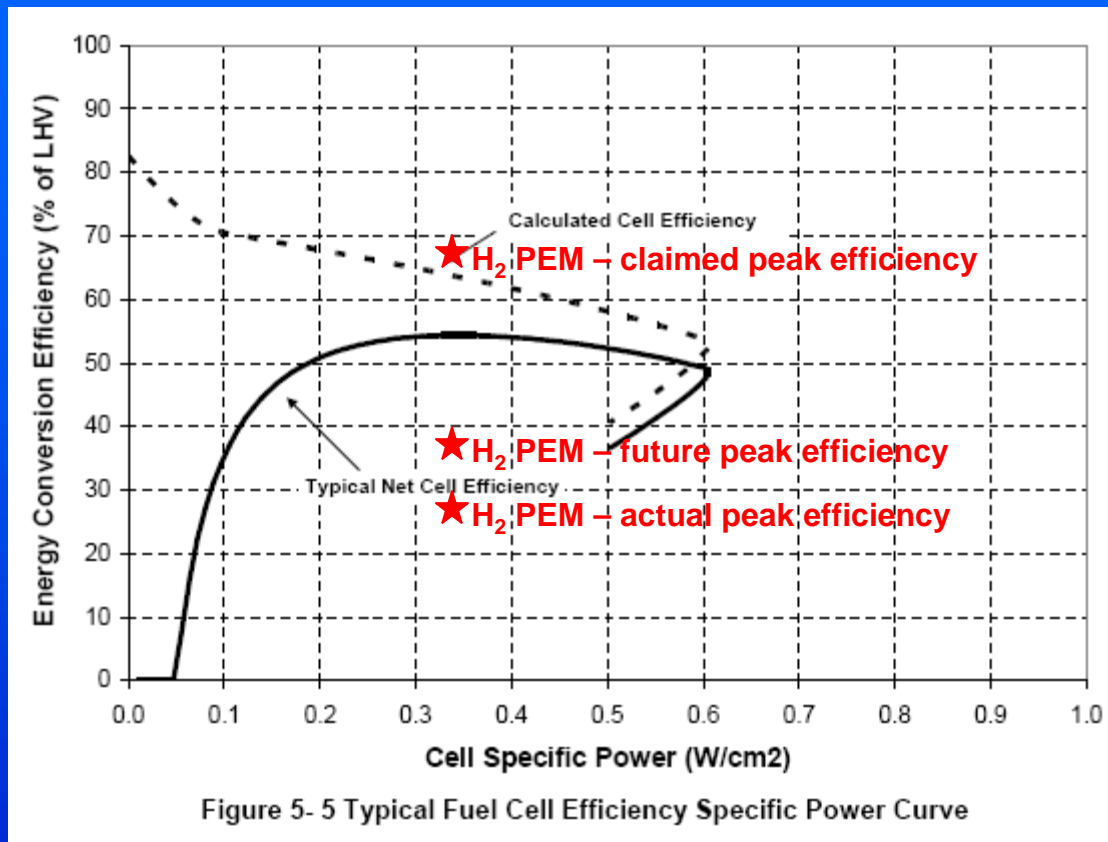
# Hydrogen Fuel Cells <sup>vs</sup> Batteries



- Hydrogen electrical storage systems are overly complex compared to batteries.



# Interpreting H<sub>2</sub> Fuel Cell Efficiency



- Absolute peak efficiency about 82% — Unobtainable.
- Theoretical efficiency near peak about 65% — Unobtainable.
- Peak net efficiency about 55% — Peak of obtainable.
- But... What about energy losses due to manufacturing H<sub>2</sub>?

# Energy Conversion 101

1 Btu natural gas  $\xrightarrow[100\% \text{ no conversion}]{} \text{natural gas}$  1 Btu

1.5 Btu natural gas  $\xrightarrow[67\% \text{ steam methane reforming}]{} \text{H}_2 \text{ gas (+ CO}_2\text{)}$  1 Btu

- Natural gas is the cheapest source of H<sub>2</sub> (half the cost of electrolysis).
- H<sub>2</sub> gas requires 50% more natural gas (and 3x the piping) for the same useful energy.
  - High temperature fuel cells can use either fuel directly.
  - Leaving natural gas alone is the most efficient option.

1 kWh electricity  $\xrightarrow[100\% \text{ no conversion}]{} \text{electricity}$  1 kWh

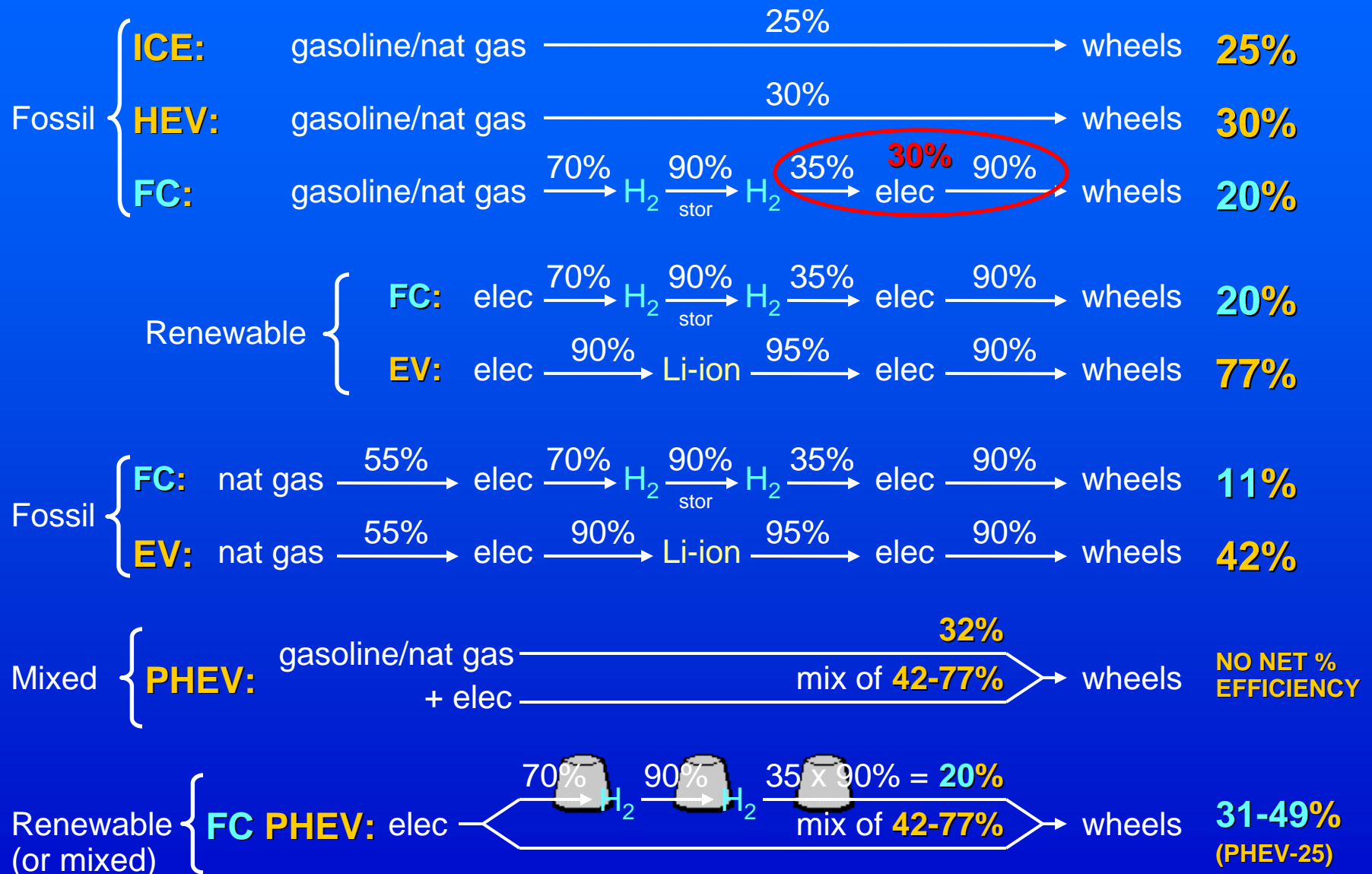
1.1 kWh electricity  $\xrightarrow[95\% \text{ charging}]{} \text{Li-ion Battery} \xrightarrow[95\% \text{ discharging}]{} \text{electricity}$  1 kWh

2 kWh electricity (+ ZnO)  $\xrightarrow[70\% \text{ electrolysis}]{} \text{Zinc} \xrightarrow[70\% \text{ fuel cell}]{} \text{electricity (+ ZnO)}$  1 kWh

4.5 kWh electricity (+ H<sub>2</sub>O)  $\xrightarrow[67\% \text{ electrolysis}]{} \text{H}_2 \text{ gas} \xrightarrow[33\% \text{ fuel cell}]{} \text{electricity (+ H}_2\text{O)}$  1 kWh

- H<sub>2</sub> fuel cells are commonly regarded as electrically efficient, but:
  - Zinc fuel cells are twice as efficient.
  - Batteries are four times as efficient.
  - Leaving electricity alone is the most efficient option.

# Fuel-to-Wheels Efficiency



# The 4:1 Energy Savings Club

Incandescent



4:1



Fluorescent

Electrolytic Hydrogen



4:1



Battery Electric Vehicle

Conventional Furnace



4:1



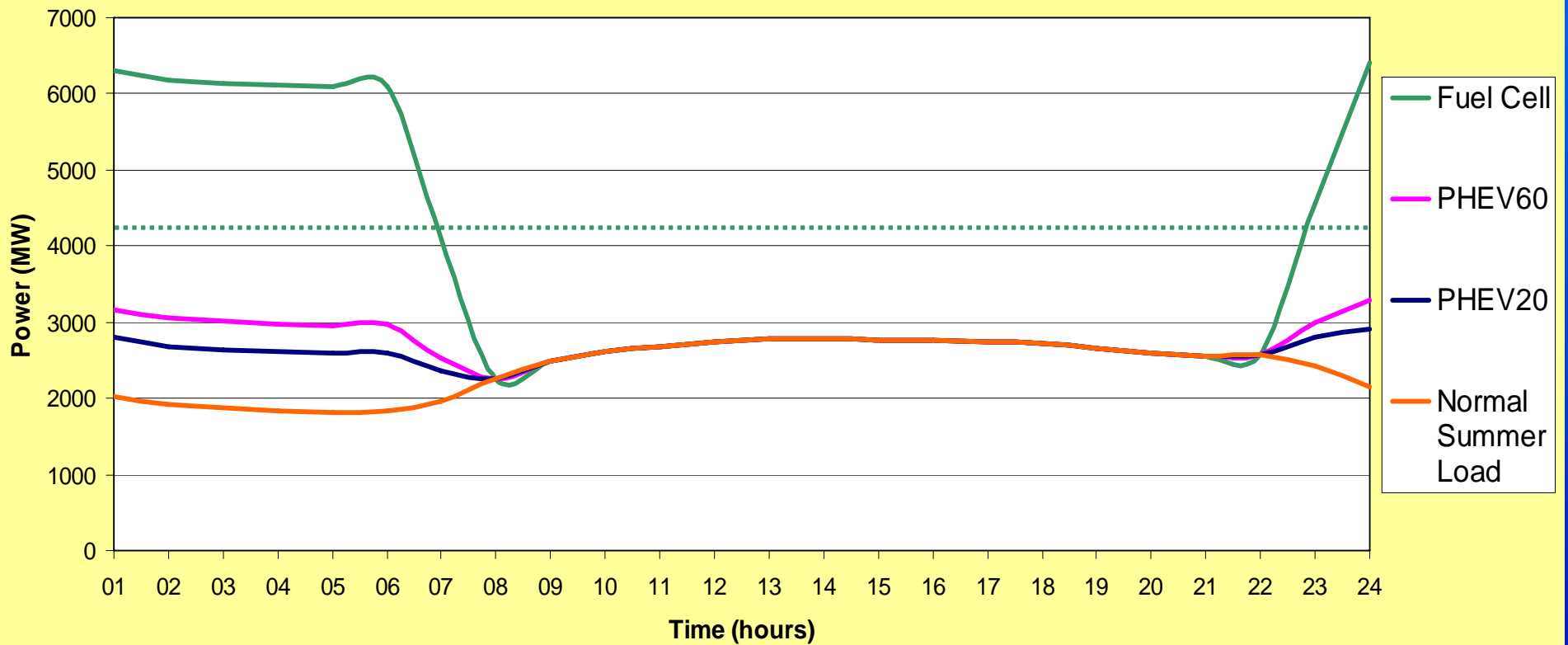
Geothermal Heat Pump

- Switching from hydrogen storage to batteries has the same energy saving advantage as:
  - switching from incandescent lamps to compact fluorescents.
  - switching from a furnace to a geothermal heat pump.







# Effects of Nighttime Charging

Charging/Fueling 620,000 Vehicles for Average Daily Driving Range



# Cost of Using Hydrogen

2003 Honda FCX	
Miles per kilogram of hydrogen	
51 city	48 hwy
Annual Fuel Cost <b>\$1515*</b>	
EPA Air Pollution Score	
Range	170 miles
Fuel	Hydrogen
Fuel Cell	Polymer Electrolyte Membrane
Motor	60 kW DC
Energy Storage Device	Ultracapacitor
*Annual fuel cost is estimated assuming 15000 miles of travel per year (55% city and 45% highway) and a fuel cost of \$5.05 per kilogram of gaseous hydrogen.	

2003 Toyota RAV4 EV Electric Vehicle	
 Possible Tax Incentives	
<a href="#">Use your Gas Prices</a>	<a href="#">Switch to Metric units</a>
Fuel Economy	
Fuel Type	Electricity
Energy Consumption(city) (kW-hrs/100 miles)	27
Energy Consumption(hwy) (kW-hrs/100 miles)	34
MPG (city)	125
MPG (highway)	100
MPG (combined)	<b>112</b>
Annual Fuel Cost @ 8¢/kWh	<b>\$362</b>

2003 Honda Civic Gasoline Cost **\$684**  
 2003 Honda Civic Gas Hybrid Cost **\$484**

2003 RAV4 2WD Gasoline Cost **\$860**

- Hydrogen cost is worse than its efficiency!
- Electrolysis twice as costly as natural gas!
  - **\$3,000** per year for hydrogen Honda FCX.

# Cost of Using Hydrogen

- \$100 billion for minimum hydrogen fuelling stations needed for large scale of hydrogen fuel cell vehicles in Canada, or...
- Any of these projects (most of them electrified):
  - 100,000 miles of single track railway electrification (eg Europe) – over 3x Canadian rail network.
  - 6,000 miles of TGV high speed electric railway – 5x French 300 km/hr network.
  - 1,500 miles of magnetic levitation high speed electric railway (eg Shanghai).
  - 12,000 miles of urban streetcar transit in boulevard.
  - 3,300 miles of urban light rail rapid transit.
  - 3,300 miles of urban busway transit (diesel powered).
  - 1,000 miles of urban monorail rapid transit.
  - 670 miles of Vancouver Skytrain rapid transit (50% tunnel, 50% elevated).
  - 430 miles of urban heavy rail subway rapid transit.
- Can also replace automobiles with PHEVs and EVs at the same time because they do not need new fuelling infrastructure.
- Fewer cars & less road congestion if public transport increased.
- Normally these options are discussed as “too expensive”.

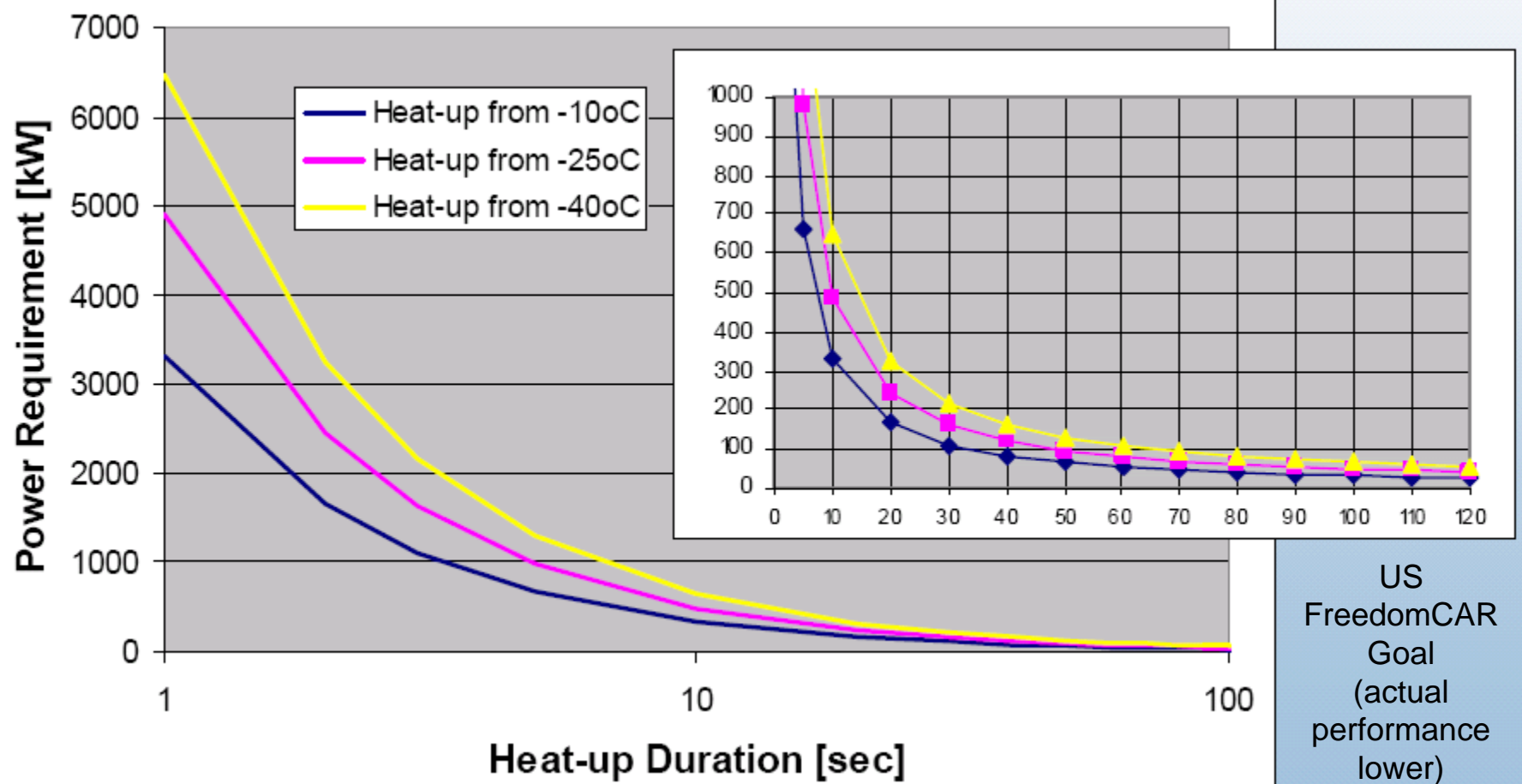
# Cost of Hydrogen Bus Fuel

- \$20 million for fuel for 20 fuel cell buses (for only 6 years), or...
- Any of these projects (most of them electrified) cost about the same:

- 20 miles of single track railway electrification (3.3 miles per year).
- 2.5 miles of urban streetcar transit in boulevard.
- 0.7 miles of urban light rail rapid transit.
- 0.7 miles of urban busway transit (diesel powered).
- 0 miles of urban busway transit (hydrogen powered).
- Enough diesel fuel for 160 Winnipeg Transit buses (1/3 of fleet).
- Enough electricity for 500 Vancouver trolley buses.
- Enough electricity to operate all Vancouver trolley buses (228) for 13 years.
- 18 miles of two-way overhead trolley bus wiring.
- Enough electricity to operate all Vancouver trolley buses (228) for 6 years **plus** 10 miles of two-way overhead wiring.
- Construction of 1000 heated bus shelters.

- Fewer cars & less road congestion if public transport increased.
- Normally these options are discussed as “too expensive”.

# PEM Cold Weather Starting



US  
FreedomCAR  
Goal  
(actual  
performance  
lower)

Start-up From -20°C	30 s	10 s	5 s
Proposed Energy Required	1.4 kWh	1.4 kWh	1.4 kWh
Power Required	167 kW	500 kW	1,000 kW
Lost Mileage	5 mi	5 mi	5 mi

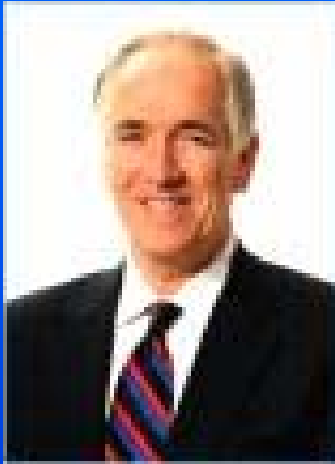
JIM BREMAN / KINCINNATI ENERGETICS PER 03/05

NATURALLY, OUR  
PROTOTYPE FOR THE  
HYDROGEN CAR  
STILL HAS SOME  
BUGS TO  
WORK OUT...





# From the Horse's Mouth...

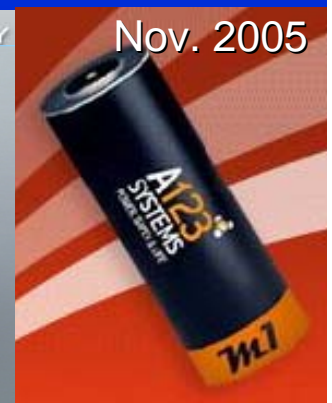
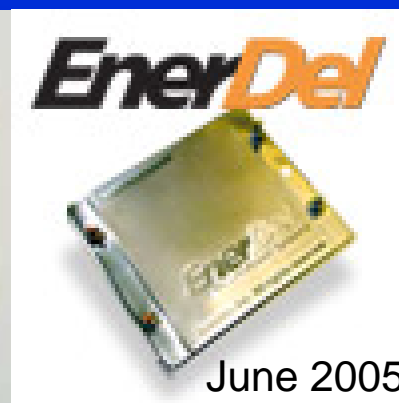


“To be honest, the only thing that could change the game is if someone invented a battery that had a range of 400 miles and could be recharged in five minutes.

***You wouldn't need a fuel cell.***

While battery technology is improving, *it's not going to happen.*”

Outgoing Ballard CEO Dennis Campbell  
(December 2005)



# ...disruptive technology!

## Altairnano's Demo EV



Converting Vehicle to a Long Range EV

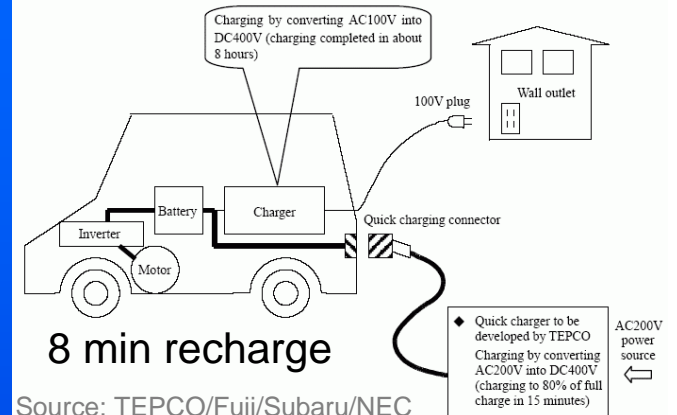
~US\$70,000



Source: Altairnano/Phoenix Motorcars

~200 Mile Range, ~10 Minute Recharge Capable

“To be honest, the only thing that could change the game is if someone invented a battery that had.....”

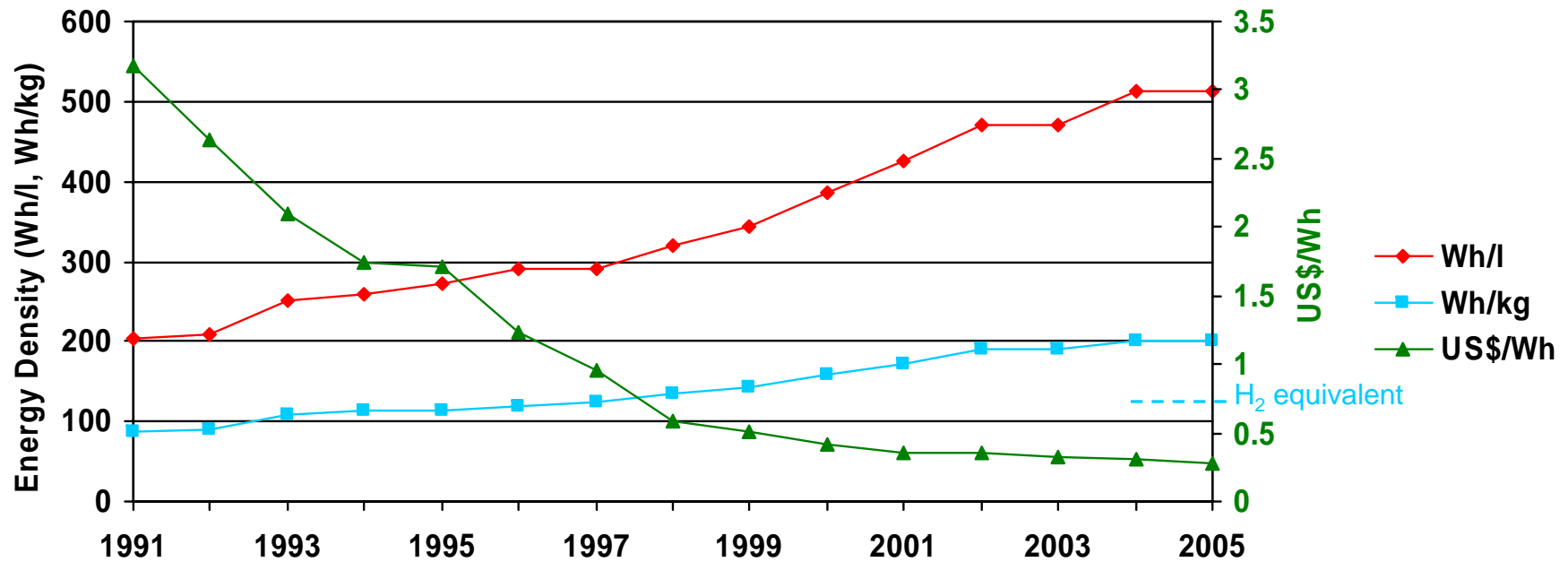


Source: TEPCO/Fuji/Subaru/NEC



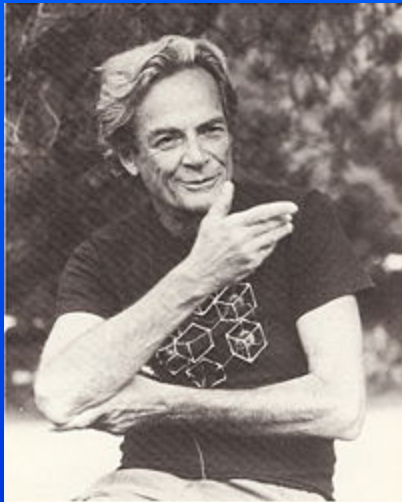
# Battery Technology

## Li-ion Battery Development



- Batteries are overdue for a new image!
  - 230% increase in energy storage density in 15 years!
  - 91% reduction in cost in 15 years!
  - Improvements still occurring:
    - 300-400 Wh/kg & 750-1000 Wh/l possible in 10 years.
    - 1000 Wh/kg possible with Li-air.

# On Successful Technology...



“For a successful technology,  
reality must take precedence  
over public relations, because  
nature cannot be fooled.”

physicist Richard Feynmann  
1918-1988

in the Challenger disaster commission report

# Fuel Cell Vehicles



- Fuel cell vehicle image may be over inflated!
  - 0 to 60 mph in 16 seconds!
  - 168 mile range (on 3.1 kg of 10,000 psi hydrogen).
  - Only a 2½ year lifespan! (source: GM 2006)
  - Does not operate in winter!

# Battery Electric Vehicles



- Tesla Roadster:
  - 0 to 60 mph in under 4 seconds! 0-60-0 in 9 seconds!
  - 240 mile range! ...at 1¢ per mile.
  - 30 kWh battery life 100,000 miles.
  - Rear wheel drive, with inline motor and 2-speed transmission.
  - US\$92,000 for fully-optioned car.
  - Fall 2007 model sold out in 4 months. (200 cars @ 100% deposit.)
- 2<sup>nd</sup> phase car a US\$40-50,000 sedan with same range in 2009.

# Series PHEV with Motor-In-Wheel



- PML Flightlink Mini QED proof-of-concept vehicles:
  - 0 to 60 mph in 4.5 seconds in pure EV mode!
  - 200-250 mile pure EV range! 932 mile total range with gas.
  - 250cc generator with four 160 hp electric motors—one in each wheel.
  - 21 kWh battery with 11 Farad ultracapacitor.
  - No transmission or mechanical drive train, saving space.
  - No mechanical brakes—640 hp electric braking!
  - Full time electronic traction control, anti-skid, and ABS.

# Photo-Voltaic Hybrid



- Solatec kit costs \$2,600 (without installation).
- Averages 10% improvement in fuel economy.
- Integrate with PHEV?

# Manitoba V2G – Vehicle To Grid

- Assume:

- 620,000 vehicles in MB.
- 1/2 are V2G-capable.
- 1/2 are plugged-in.
- 1/2 of battery capacity is available.

- If EnergyCS PHEV-30s:

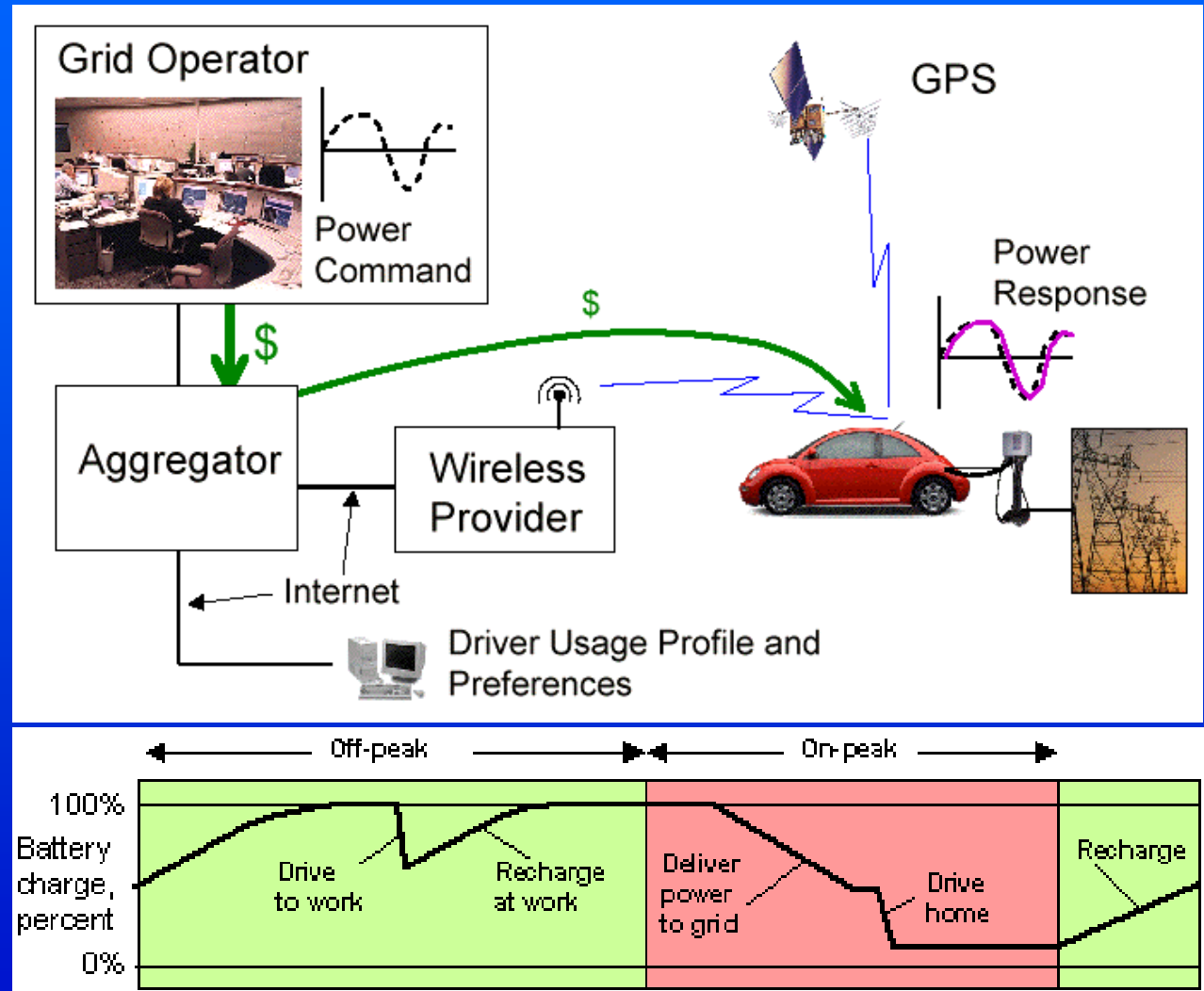
- 1 kW (10 kW), 9kWh
- V2G power = 160 MW
- V2G energy = 700 MWh

- If Tesla Roadster EVs:

- 20 kW (200 kW), 50 kWh
- V2G power = 3,100 MW
- V2G energy = 3,900 MWh

- Substantial “free” balancing resource.

- Peak shaving.
- Load following.
- 50% wind penetration!?
- Revenue for driver?

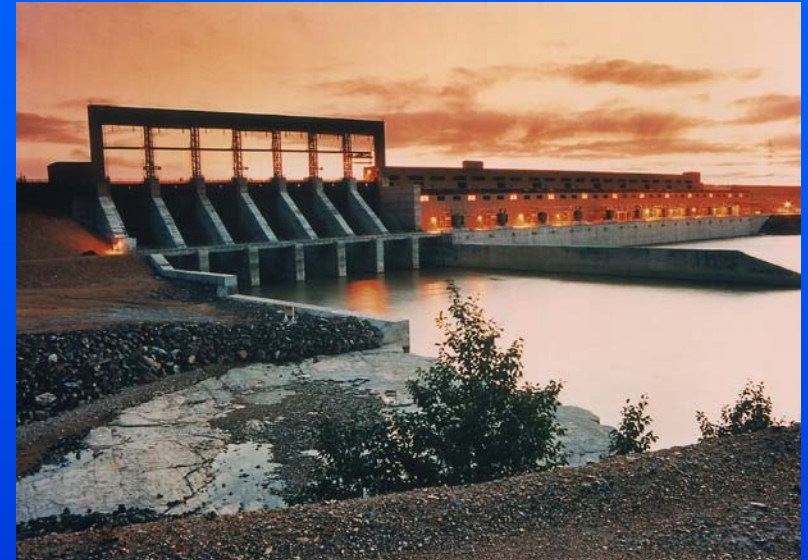
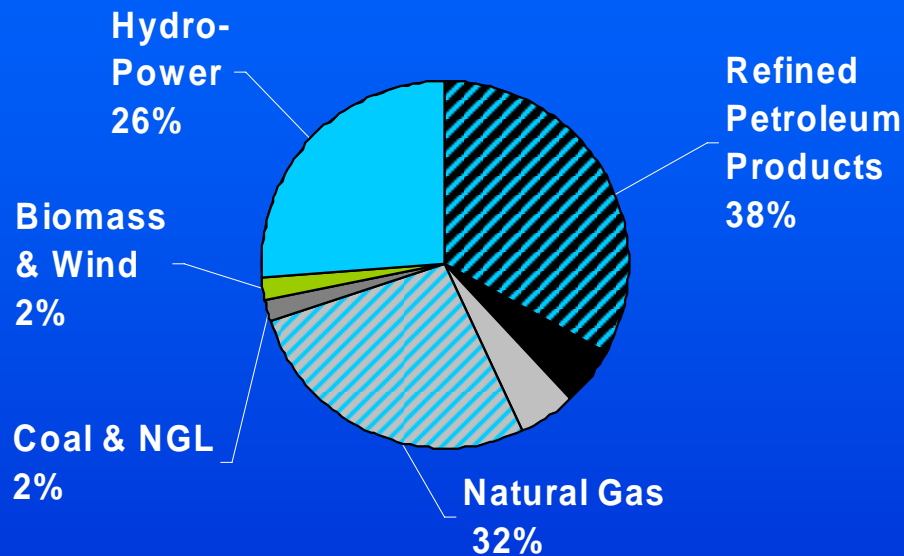


**THE END** is coming!



# Energy Consumption in Manitoba

- **By Fuel:**



- Total consumption  $\approx 256,000$  TJ  $\approx 71$  TWh.
- Exports (relative to 100% of consumption):
  - 15% Hydroelectricity. ( $\rightarrow$  potential substitute for 60% oil & gas)
  - 8% Crude petroleum.
- Goal: increase clean & green; reduce fossil fuels.



# Hydrogen Bus <sup>vs</sup> Zinc Bus

## H<sub>2</sub>-Air FC Bus

- 20% efficient\*
- FC does not work below +3°C
- H<sub>2</sub> in roof tanks



## Zn-Air FC Bus

- 50% efficient\*
- Operates from -40°C to +50°C
- Zn underneath



\* closed loop efficiencies for electrolysis + fuel cell only

\* by comparison, Li-ion batteries are about 95% efficient

# Hydrogen Bus vs Trolley Bus

## H<sub>2</sub>-Air FC Bus

- 20% efficient
- FC does not work below +3°C
- H<sub>2</sub> in roof tanks



## Trolley Bus

- 100% efficient
- Operates from -60°C to +50°C
- No fuel weight



Source: Tom's Trolley Bus Pictures, Winnipeg

- Closed loop efficiency for H<sub>2</sub> electrolysis + fuel cell only (worse with handling and storage)
- Trolley is lighter weight and has no conversion losses
- Both depend on oil (tires & asphalt)

# Trolley Buses Without Wires

## Super-Cap Bus

- 85% efficient\*
- Operates from  $-60^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$
- Supercapacitors



Source:  
Zachary  
Jiang,  
June, 2005

## Gyrobuss

- 70% efficient\*
- Operates from  $-40^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$
- Flywheel-motor-generator



Source: Noel Reed, Aug 24, 1958

\* capacitor efficiency depends on external circuit resistance

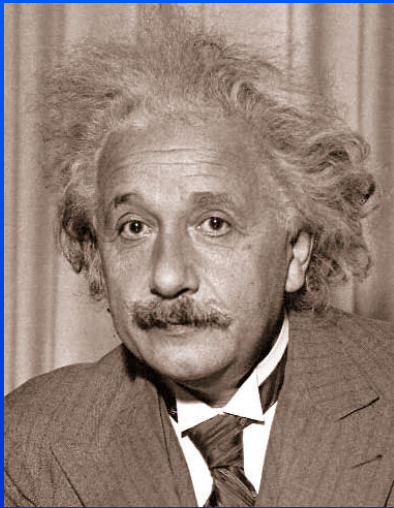
\* by comparison, Li-ion batteries are about 95% efficient

# No Oil Required!



- 18% of the energy use per passenger of diesel buses:
  - Near 100% electrical efficiency due to overhead pickup wire.
  - Low rolling resistance losses compared to tires. (400% efficient?)
- Operates in any climate.
- No oil required for tires or roadway.

# One Last Thought...



“You can’t solve a problem with the same kind of thinking that created it.”

Albert Einstein 1879-1955



# Thank You! PHEV Research Project

Presented to APEGM

February 15, 2008 by

Ed Innes , BScEE, MSc(EE)

**Emerging Energy Systems**

[www.125mpg.com](http://www.125mpg.com)



# Questions?

[www.125mpg.com](http://www.125mpg.com)

# PHEV2007 Conference

## WHERE THE GRID MEETS THE ROAD

Winnipeg, Manitoba  November 1 & 2, 2007

DOWNLOAD  
BROCHURE

Delta Winnipeg  
350 St. Mary Ave.

# [www.pluginhighway.ca](http://www.pluginhighway.ca)

### Sponsors

NSERC/Manitoba Hydro  
Alternative Energy  
Industrial Chair



The Centre for  
Sustainable  
Transportation

Le Centre pour  
un transport  
durable

AT THE UNIVERSITY OF WINNIPEG



UNIVERSITY  
OF MANITOBA

Manitoba   
Infrastructure and Transportation



Electric  
Mobility  
Canada

Mobilité  
électrique  
Canada

### Conference highlights included:

- PHEV & PEV research network development,
- Advanced battery technologies,
- Vehicle-to-grid applications,
- PHEV enhancement of renewable energy,
- Review of on-going PHEV and PEV demonstrations,
- Vehicle simulation courses by leading experts,
- Development of a PHEV bus demonstration project,
- Tour of New Flyer hybrid bus manufacturing plant,
- PHEV public education forum.
- Display of PHEVs and batteries.



[www.125mpg.com](http://www.125mpg.com)