Energy Usage Considerations of Electric Drive Vehicles

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Why Electric Drive Vehicles?

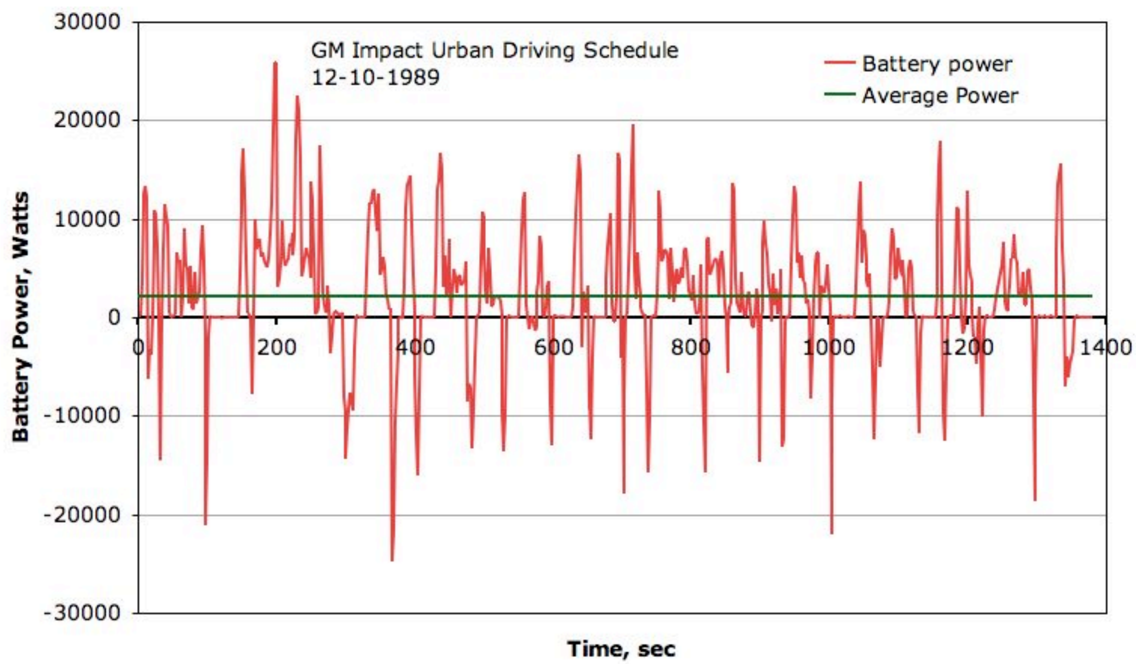
- Some or all of tractive power provided from electric motor
- Bidirectional torque - able to recapture kinetic energy during braking and recapture potential energy when descending a hill
- Motor runs on electricity - opens up potential for other sources of energy than petroleum-based fuels
- Rationale for adopting electric drive
  - Emissions
    - Criteria pollutants
    - Greenhouse gas
  - Energy Security
  - Energy Efficiency

Types of Electric Drive Vehicles and Fuels

- Battery EV
  - Electricity
- Hybrid
  - Gasoline, Diesel
  - Natural Gas
  - Renewable Liquid fuel
  - Hydrogen
- Plug-in Hybrid
  - Adds electricity to fuel-only hybrid
- Fuel Cell
  - Hydrogen
    - Natural gas
    - Electricity
    - Other

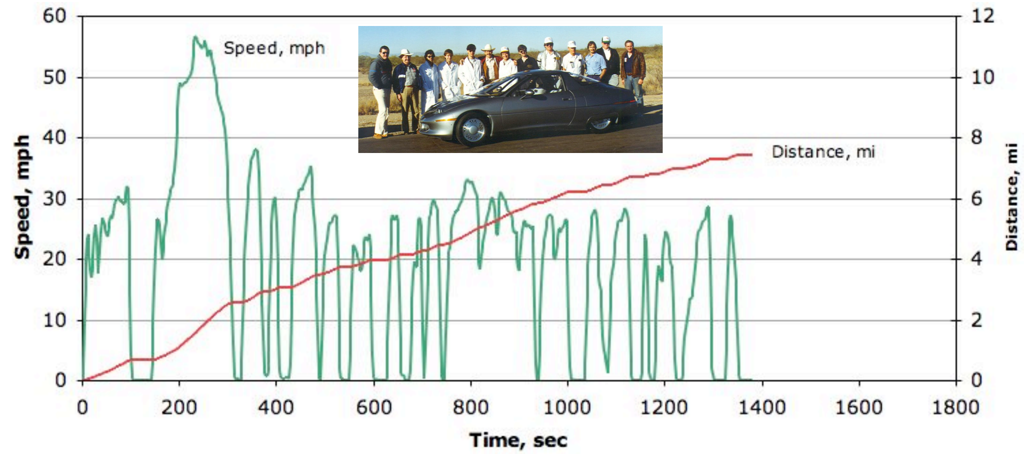
Vehicle Power Profile

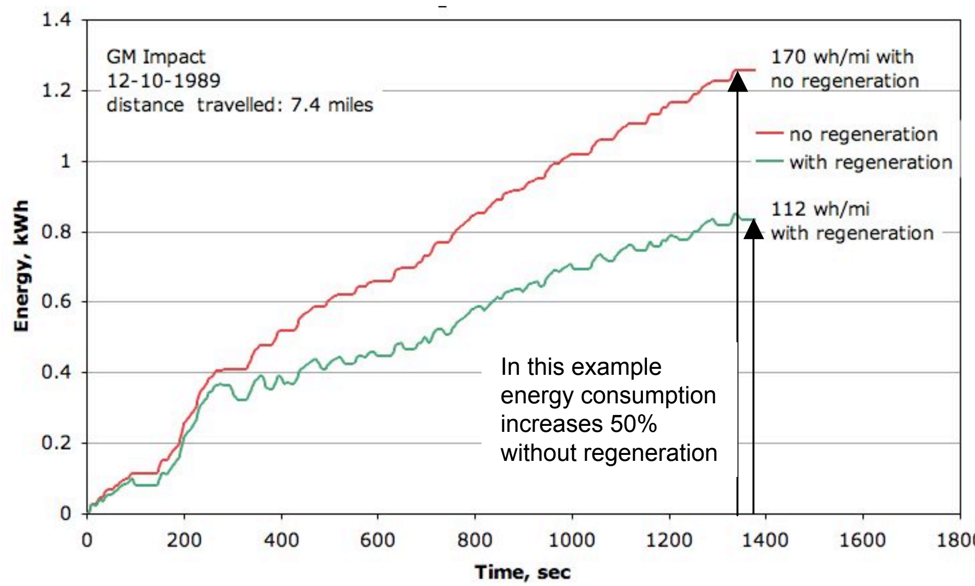
- Vehicle power profile in urban driving characterized by high peaks (positive and negative), and low average power
- Not well matched to conventional ICE drivetrain
  - Poor average engine efficiency
  - No recapture of energy while slowing; lost as heat in brakes



Regenerative Energy Capture

- Electric drive allows recapture of kinetic energy when slowing or recapture of potential energy when descending a hill
- Energy storage requirements:
  - big enough to store energy from hills
  - High power acceptance
- With the right combination of electric motor and energy storage, friction brakes are not used in normal driving

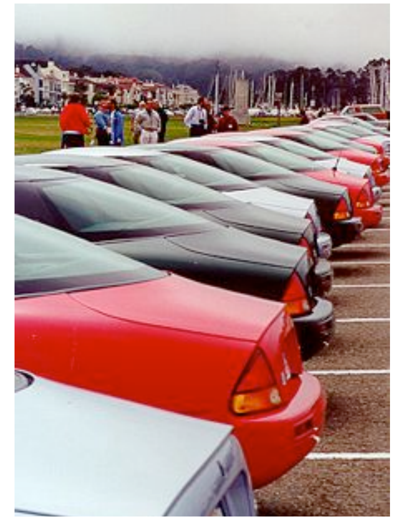




Significant Electric Drive Milestones/Activities in California since 1990

1990	GM Impact debut at LA Auto Show
1990	CARB adopts ZEV mandate
1996	CARB and automakers adopt MOA
1996	GM EV1 available for lease
1997	Other EVs become available, most only to fleets
2001	First hybrids to market, Prius and Insight
2002	Toyota briefly offers RAV4EV for sale
2002	ZEV mandate shifts away from EVs to fuel cell vehicle demonstration projects
2003	Some RAV4EVs exceed 100,000 miles on original battery packs
2004	GM takes back EV1s, crushes them
2004	Governor's executive order to build the "hydrogen highway"
2005	EV1 enthusiasts hold 24/7 vigil at EV1 storage site
2005	California legislature appropriates funds to start building hydrogen highway

EV and FCV Events and Rallies



EV events usually organized by drivers

FCV events carefully scripted and stage managed; “Rally thru the Valley”, “Crusin’ Southern Cal”

EVs in daily use by fleets and public; CARB tracks ongoing progress

100,000-mile RAV4 EVs in 2003

Popular EV parking at LAX

CARB board meeting

CARB ZEV workshop

RIP EV1


4AWB836


Save the EV1s!
Zero Emissions NOW!
GM
Destroying Tomorrow's EVs today.
EV RIDR

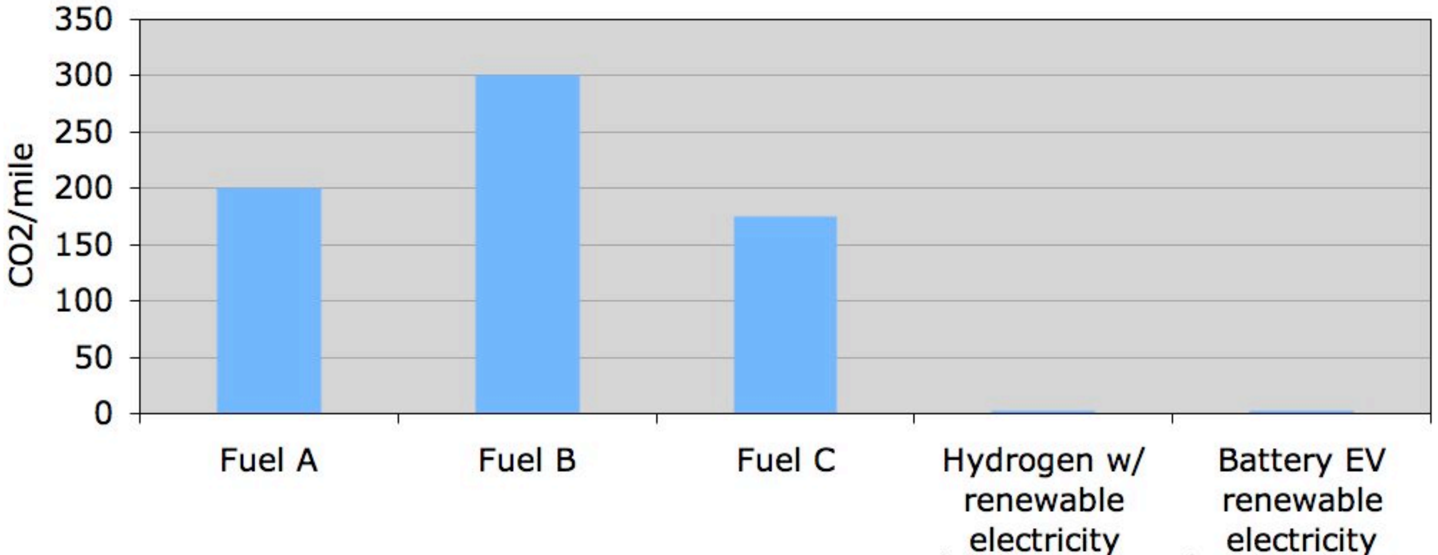

CARS
SHOULD
BE
CLEAN

What Happened?

- 1996 MOA between CARB and Automakers
  - Required advanced batteries, rather than specific vehicle performance; penalized efficient purpose-built EV1 which worked well with lead acid batteries (Advanced battery added $40K to manufacturing cost of EV1)
  - Ambiguous language of MOA
    - "Manufacturer commits that it will have the capacity to produce specified numbers of ZEVs that could be sold in California if warranted by customer demand"
- California picked the least practical approach (hydrogen) for attention/funding, just as other alternatives were on the verge of becoming practical
- Aimed for a solution which was thought to be the best for the long term instead of incremental improvement of nearer-term demonstrated successes

How Do We Account for the Environmental Footprint of Vehicle Alternatives?

- Is it enough to say that an option is green just because it can be fuelled with renewable energy? It matters <u>how much</u> renewable energy it takes!
- How to factor in the opportunity cost of using renewable energy?



Both show zero greenhouse gas per mile when powered by renewable electricity -- but do both have the same environmental footprint? This graph gives no indication as to <u>how much</u> renewable electricity each option uses.

Hydrogen

- Hydrogen is an energy carrier made from other sources of energy - principally natural gas and electricity
- Natural gas and electricity work well directly in vehicles
- There needs to be a compelling reason to go through the trouble of converting natural gas or electricity to hydrogen to use in a vehicle, rather than using these energy sources directly in vehicles

Hydrogen Made with Electricity

- 65 kWh per kg : Stuart datasheet, and as derived from Honda's published data on solar hydrogen station
  - Includes electrolysis and compression
- In a fuel cell, 1 kg of hydrogen produces about 16 kWh of electricity to drive the wheels (~ 50% efficiency)
- 65 kWh in; 16 kWh out
  Overall efficiency 25%;

75% of input energy is lost

Fuel Cell Vehicle Uses Four Times as Much Electricity per Mile as EV

56.5 miles/kg H2

65 kWh/kg

30 kWh/100mi

1.15 kWh/mi ⟷ 0.3 kWh/mi

2006 Fuel Cell Vehicles

	Honda FCX
Compare Side-by-Side	
Fuel Economy	
City (miles/kg)	62
Highway (miles/kg)	51
Range	190 miles
Vehicle Characteristics[1]	
Vehicle Class	Subcompact
Fuel Type	Hydrogen
Motor	80 kW DC Brushless
Type of Fuel Cell	PEM
Energy Storage Device	Ultra Capacitor 9.2 farad
Availability[2]	Lease only - 50 states

2003 Toyota RAV4 EV

Electric Vehicle

Possible Tax Incentives

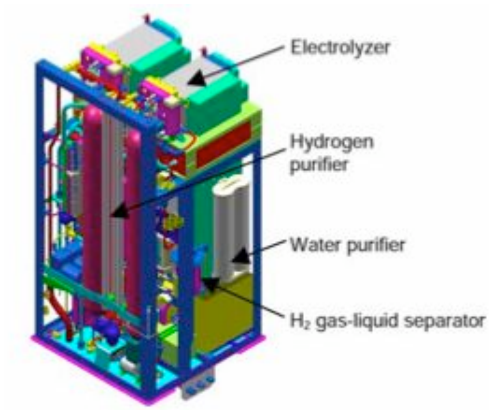
Use your Gas Prices

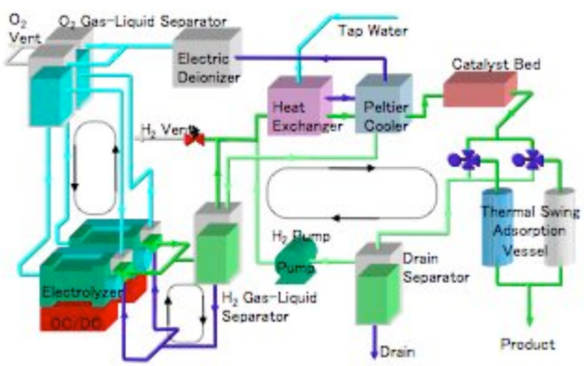
Switch to Metric units

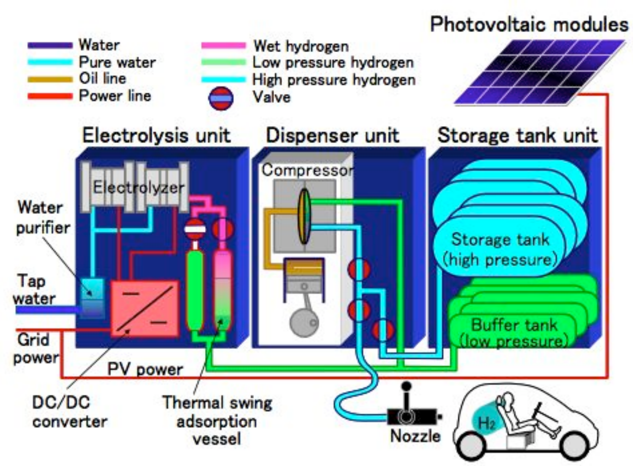
Fuel Economy	
Fuel Type	Electricity
Energy Consumption(city) (kW-hrs/100 miles)	27
Energy Consumption(hwy) (kW-hrs/100 miles)	34
MPG (city)	125
MPG (highway)	100
MPG (combined)	112
Annual Fuel Cost	$362

Honda Solar Hydrogen Station

32 kWh/day solar energy to produces hydrogen, provides 28 miles with zero CO2







Better Use of 32 kWh/day Solar Energy

32 kWh
28 miles

FCEV

Run your car
Zero CO2

or

8.4 kWh
28 miles

EV or Plug-in HEV

+

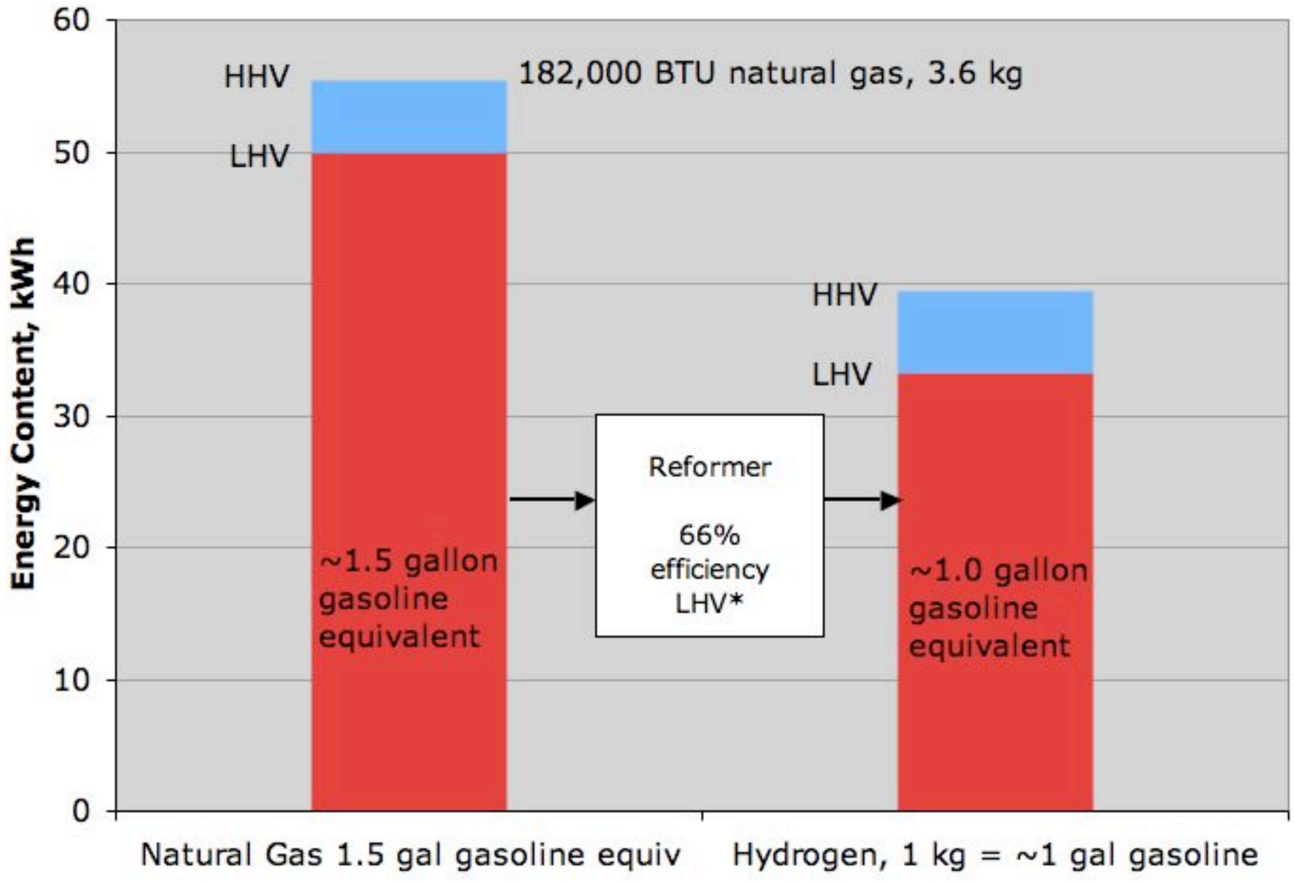
23.6 kWh
Run household loads

1. Run ten compact fluorescent light bulbs for 5 hours
2. Provide the daily energy needs of the refrigerator
3. Run the television for 4 hours
4. Run the computer for 4 hours
5. Run the dishes through the dishwasher, including electrically heating the water
6. Run a load of laundry through the washer, including electrically heating the water
7. Dry the load of laundry (gas dryer)
8. Heat water for four showers
9. Run a 3-ton (36000 btu/h) central air conditioner for 5 hours

Run your car AND your house
Negative 10 kg CO2

Hydrogen made with Natural Gas

- Some energy lost converting natural gas to hydrogen



* CA H2 Net Societal Benefits team report, 2010 scenario for on-site NG steam reforming data results in only 60.6% of NG LHV converted to H2 LHV if the required electricity for the process is produced with 8500BTU/kWh NG powerplant

Fuel Cell Vehicle vs. CNG Hybrid

Start with 3.6 kg natural gas

Reform NG
Into hydrogen

Use NG
Directly in vehicle

1 kg hydrogen	3.6 kg natural gas
	
Honda FCX FCV (EPA size class: subcompact) 3713 lb empty weight 56.5 miles/kg	Bi Fuel Prius II CNG* EPA size class: midsize 3196 lb empty weight 3.4 kg/100km (combined) 18.3 m/kg natural gas
56.5 miles ⟵⟶	65.9 miles

* (Holdigaz SA &Gaznat SA Switzerland)

Plug in Hybrid Vehicles
How Important is "ZEV" Range?

- A plug-in hybrid is conventionally thought of as having some driving range (say 30 miles) on battery power only
- However, most of the benefits of offsetting petroleum-based fuels with electricity can be realized with a low-power battery pack working together with the engine
  - Battery pack provides low power engine-off driving around town
  - Engine kicks in to provide high power
  - Battery and engine split the load on highway
- This approach places far less demand on the battery than a vehicle capable of full-performance EV-mode operation
- A 6kWh lithium ion battery (40kg, $2700) could offset ~half of daily gasoline use in a plug-in Prius
  - 5kWh daily energy offsets gasoline sufficient for 18 miles, half of 36 miles/daily use (13k miles/year)
- Example of this type of vehicle: Energy CS / EDrive Systems Prius

EDrive Systems

ZEV Progress over the Last Decade (?)

1997: A-Class EV
Range: 125 miles
(>180 miles w/current
Battery technology)

Electricity use: 300 Wh/mile

2006: A-Class Fuel Cell Vehicle
Range: 110 miles

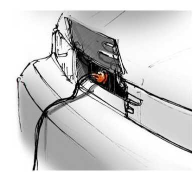
Electricity use: 1130 Wh/mile

Some Future Electric Vehicles

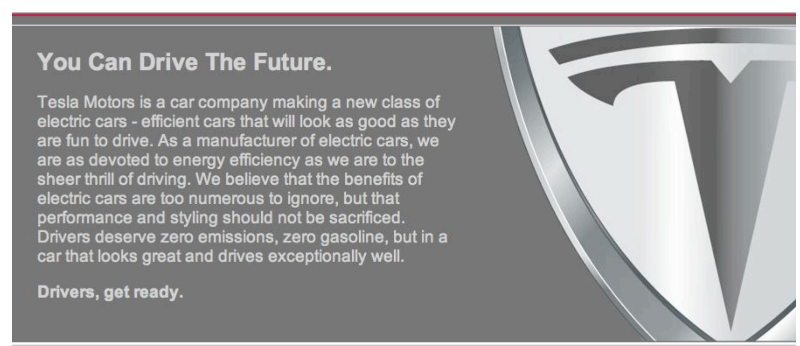
- Subaru R1e
  - 10-vehicle demo fleet in Japan
  - Lithium ion fast charge

- Mitsubishi MIEV
  - Lithium battery
  - Wheel motors

- AC Propulsion EV
  - Lithium ion, 150-200 mile range
  - V2G ready

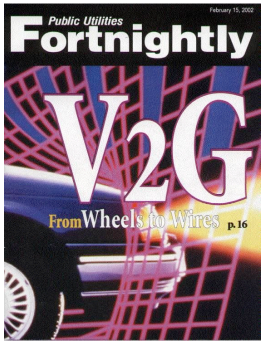


- Tesla Motors
  - EV startup San Carlos CA
  - "Drivers deserve zero emissions, zero gasoline, but in a car that looks great and drives exceptionally well. Drivers, get ready."

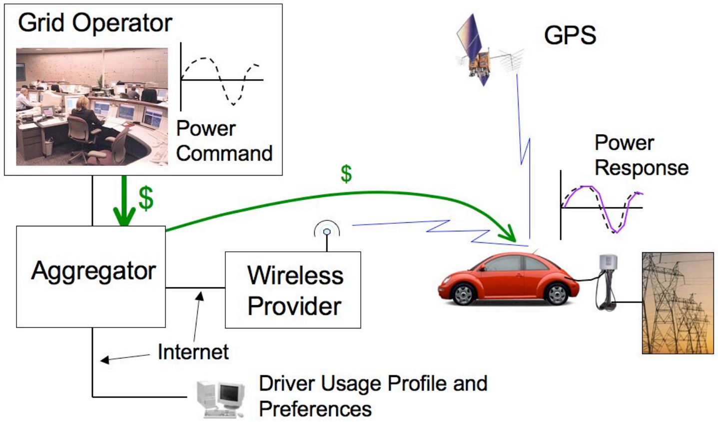


Vehicle to Grid "V2G"

- Vehicles in use about 1-2 hours/day, parked 22-23 hours/day
- Idle vehicles connected to the grid can perform ancillary services for grid operator, creating value
  - Commanded wirelessly
- Most valuable service is Regulation - the continuous matching of generation and load
  - Regulation needed 24/7, 4 second update rate
  - CARB sponsored successful AC Propulsion V2G demo project in 2002, Cal ISO participated
- V2G usually considered bi-directional power -to and from grid, but initial rollout can be simplified by keeping power unidirectional (i.e. grid operator remotely controls battery charger power drawn from grid)
- V2G can be a good match to intermittent renewables (wind, solar), enabling larger penetration of renewables on the power grid

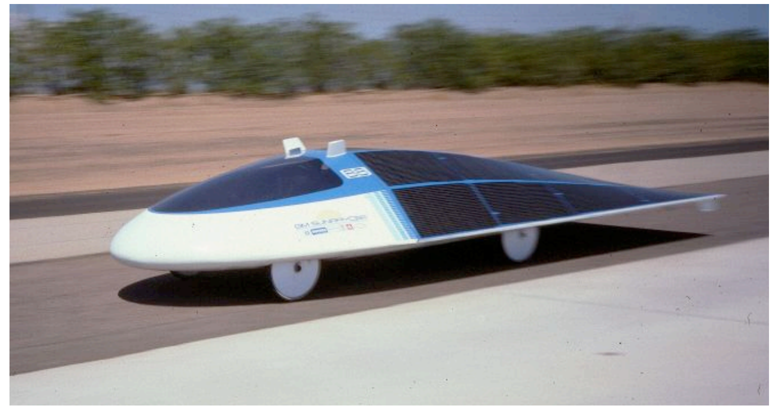


Grid Regulation with an EV or HEV



Does Solar Make Sense ON Vehicles?

- Conventional wisdom is that solar power not suited for cars
- But added to plug-in hybrid or EV may make sense
  - 1.5 sq meters, 300W rated
  - $4/W installed in high volume
  - $1200 option
  - 1.5 kWh/day energy capture
  - Provides 5 miles daily, offsets 0.1 gallons, or $0.30 @ $3.00/gal
    - Provides 14% of energy for 13k miles/year usage
    - Energy value $0.20/kWh
  - Pays for itself in 11 years



1987 GM Sunraycer, 50 mph direct solar

2005 Solar-assist Prius

When Does Hydrogen Make Sense?

- When all electricity is created with zero greenhouse gas emissions
- When there is surplus electricity for which there is no other use
- If a zero CO_2 method of hydrogen production is invented that uses energy sources that are not already in use.
- Long-endurance high-altitude aircraft, where the high specific energy (energy per weight) of hydrogen can be a significant benefit

- Applications that need long-duration power without combustion

My Prediction for the Future of Passenger Vehicles

- Hybrids will become the ‘standard’ type of fueled vehicle
  - Blended flex fuel capability to allow gradual shift away from petroleum-based fuels to biofuels and coal-based fuels
  - Plug-in capability will follow, becoming standard as well. Half of vehicle energy use through grid electricity
- Battery electric vehicles (BEVs) will return, with small but significant market share
  - Will be preferred by many drivers for features, drivability
  - Larger battery and charger are better for V2G; benefits of V2G will increase BEV market share
- Hydrogen very unlikely to become an automotive fuel
  - Too much energy wasted to make it
  - Too hard to store it
  - Not as good as the alternatives