The Re-Electrification of the Automobile (batteries on the path to sustainable personal transportation)

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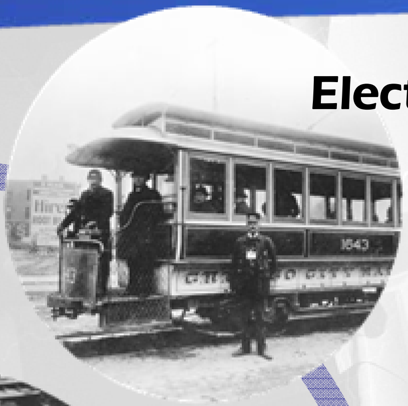
A Consumer Product Will Always Succeed or Fail on the Basis of Customer Value

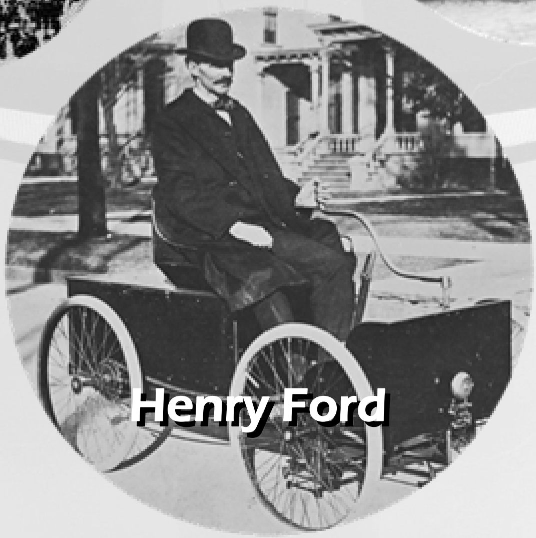
- Value: 1) a fair return or equivalent in goods, services, or money for something exchanged, 3) relative worth, utility or importance.
  - Merriam Webster's Collegiate Dictionary, 10th Edition.
- Customer Goal: emotionally satisfying, safe, comfortable personal transportation at minimum total cost.
- Societal Goal: sustainable personal transportation.

Setting the Scene 1900

Horses

Electric Train



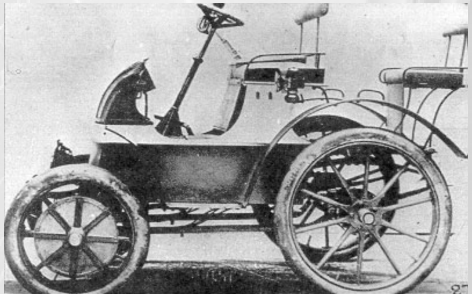


Horse Drawn
Fuel Tanker

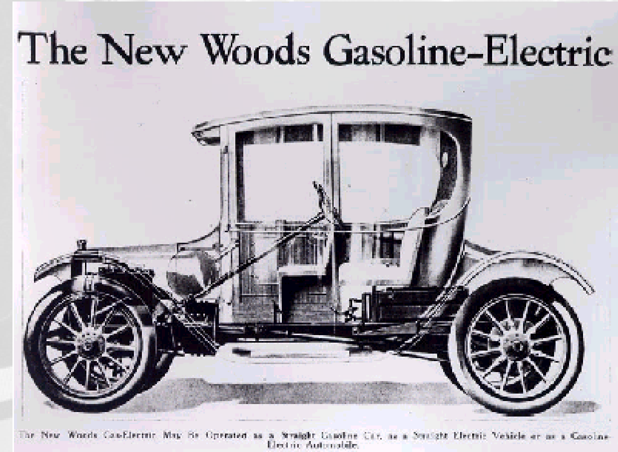
Steam Ship

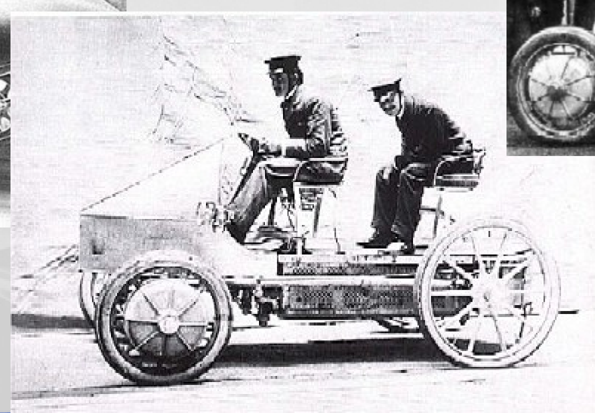
Horses

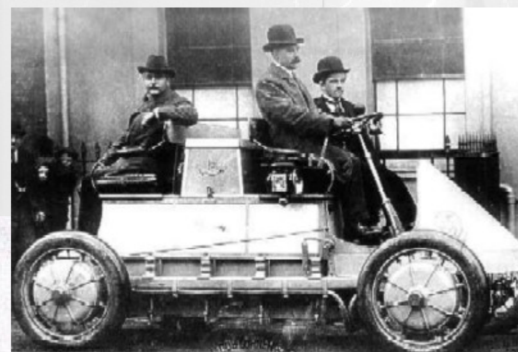
Early EVs and HEVs: Products and Record-Breakers



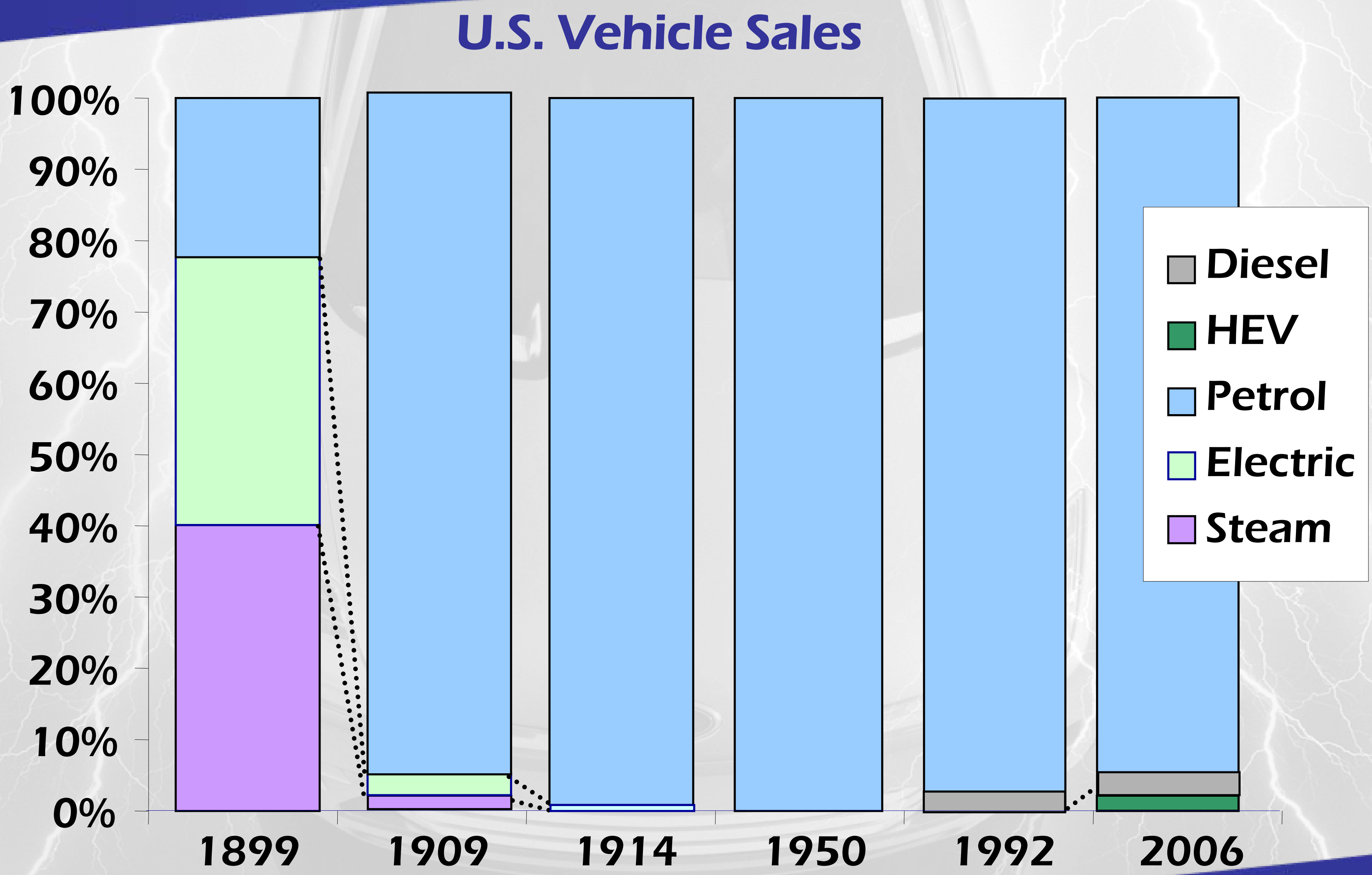
The early 1900's Lohner-Porsche, originally electric-powered, then with an internal combustion engine powering hub-mounted electric motors.







Automobile Market… then and now

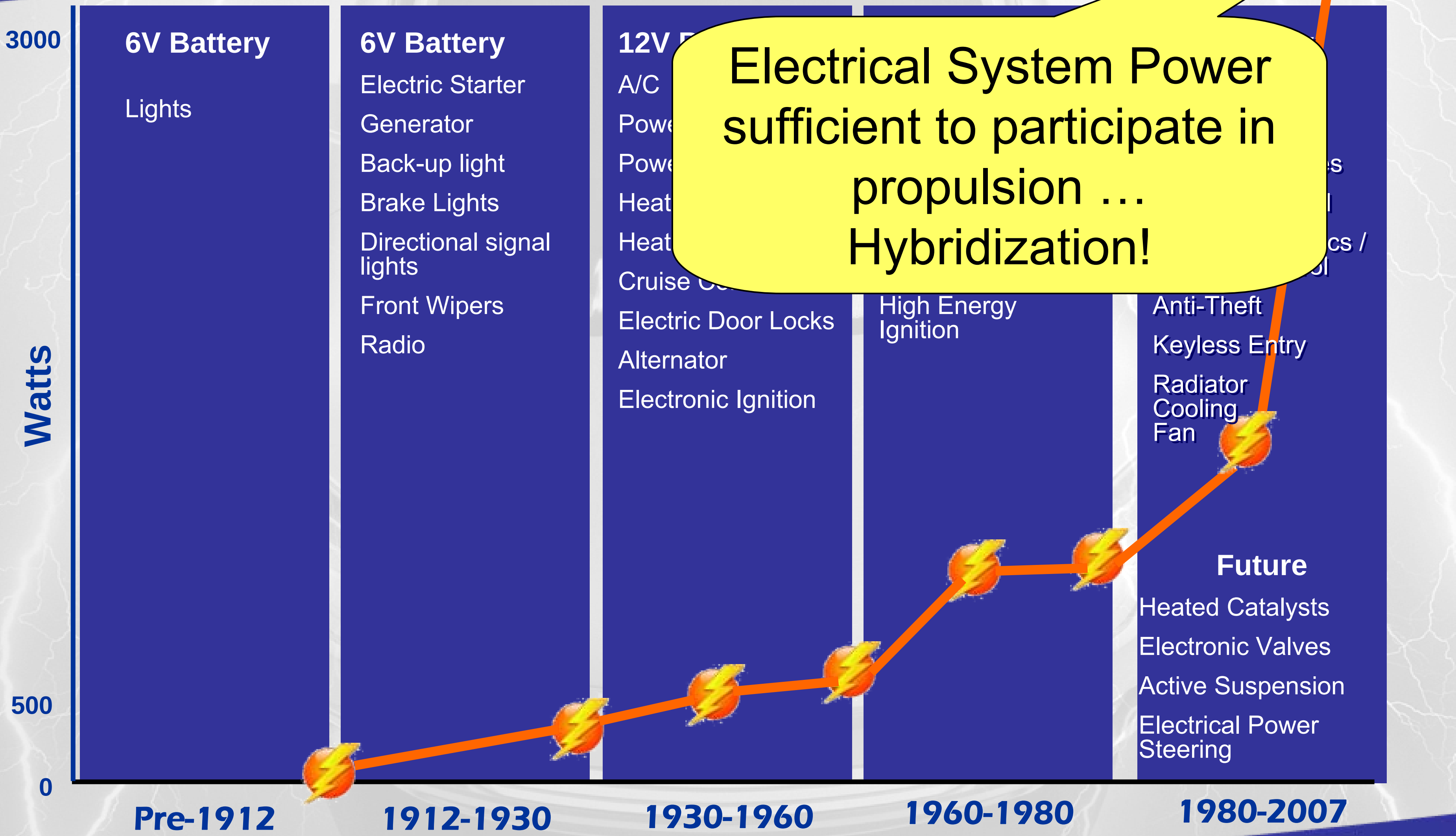


The Failed EV Renaissance

- In 1900, EVs were favored for their silence, cleanliness and ease of use.
- By 1910 they were overtaken by ICVs by virtue of:
  - Much greater range and quick “recharge”
  - Growing availability of fuel
  - Improving reliability and ease of use
  - Lower operating cost

In spite of growing concerns over global warming and energy independence, the EV “Renaissance” of 1990s failed for much the same reasons. (more later)

Electrical System Development & Power Requirements

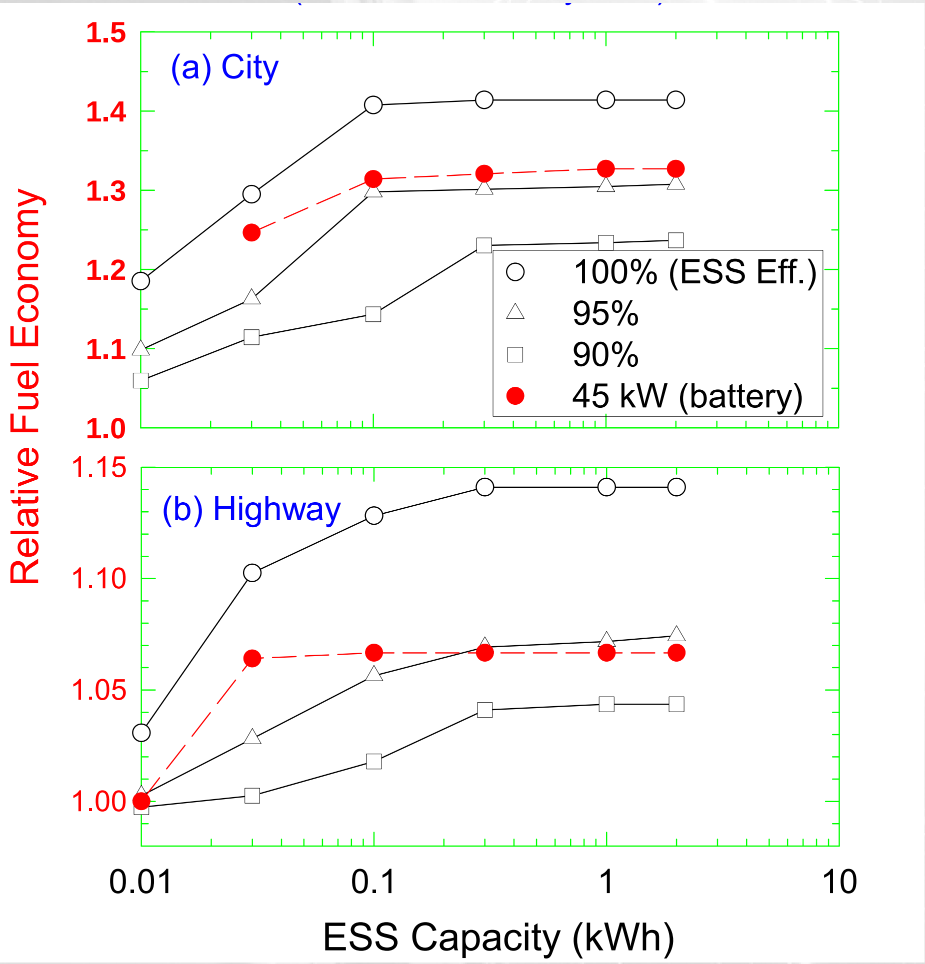


Hybrid Benefit is Very Sensitive to Usage

	Hybrid Function				Fuel Consumption Reduction			
Hybrid Type:	Stop/ start	Engine Assist	Regen Brake	E-drive	US HiWay	US City	NEDC	Japan 10-15
Micro-Hybrid 14 V Belt-ISG				NO	0%	7%	7%	12%
Mild Hybrid 42 V Belt/Crank ISG		-10% downsize		NO	4%	15%	15%	19%
Medium Hybrid		-30% downsize Atkinson		NO	16%	34%	34%	37%
Full Hybrid		-30% downsize Atkinson		YES	19%	44%	39%	45%

HEV Battery Sizing : How Little is Enough?

- Contrary to popular expectation, battery energy required to achieve hybrid efficiency benefit is very small.
  - Battery capacity sized by regenerative braking, standby loads and durability requirements.
  - No significant electric drive requirement.
- This small battery, "power hybrid" concept is the key to HEV affordability today.

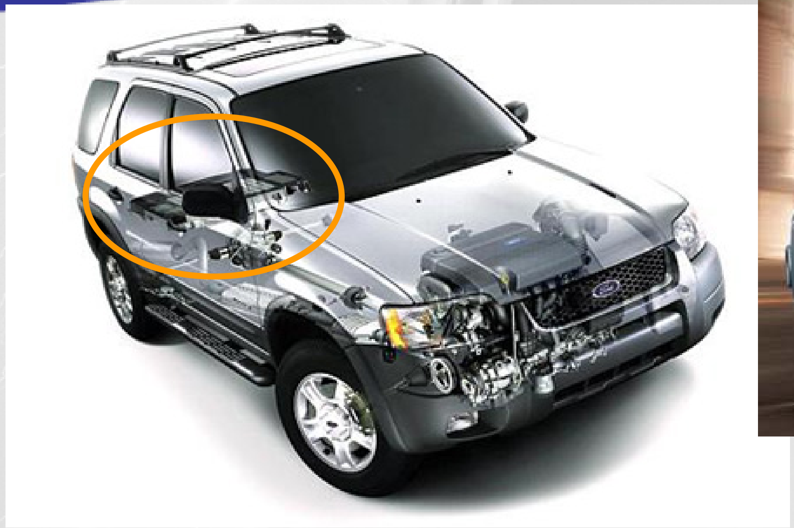


HEV Battery Requirements (Escape Hybrid)

Power/Energy Ratio	20
Energy (nominal)	2 kWh
Power	39 kW
Cycle Avg. Efficiency	>90 % (round trip)
Cycle Life	300,000 (40-60% SOC)
Calendar Life	10 years, 150,000 miles*
Operating Temperature	-30 C to 50 C
USABC Long-Term Goal (100 k/year)	$800**

*for AT-PZEV credit, battery warranted as part of emissions system
**Present cost is several times this target

A Message from Our Sponsor:



2008 Escape Hybrid

2009 Fusion Hybrid

Plug-In HEV: The Trillion Dollar Question

- Part 1: What is the net CO_2 impact of shifting propulsion energy (and emissions) from the vehicle to the grid? Impact on Energy Security?
  - **Well/mine – to – Wheels Studies**
- Part 2: How much battery is enough, and what is the net cost/benefit to the consumer?
  - **Fleet Usage Studies**

Note: While this is not a technical review, the findings of Ford internal studies are in general agreement with published reports.

200 Million LDVs x $5000*/vehicle = $1,000,000,000,000

***Cost includes battery and required vehicle actions.**

CO_2 Benefit Depends on Generating Mix

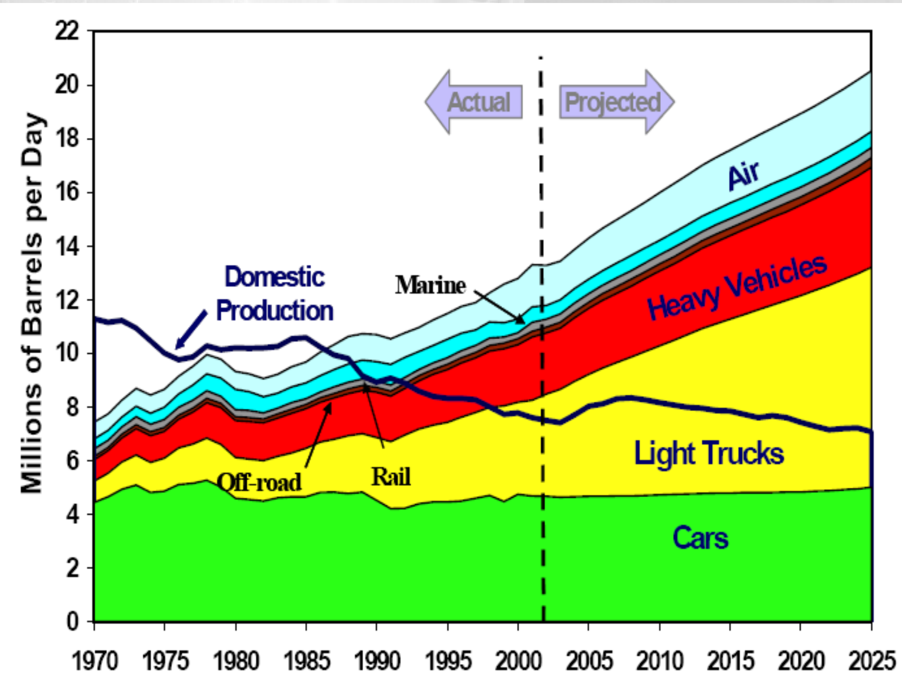
CO_2 emissions (gm/mile equivalent, "average" LDV)				
	Min	Max	Avg.	SOA
Coal	235	438	274	192
NG	149	248	192	119
Oil		388	262	
Nuclear/Renew			0	0
US Avg.			178	
HEV			296	
Conv. Veh.			432	

* Regional generating mix and dispatch orders vary widely.

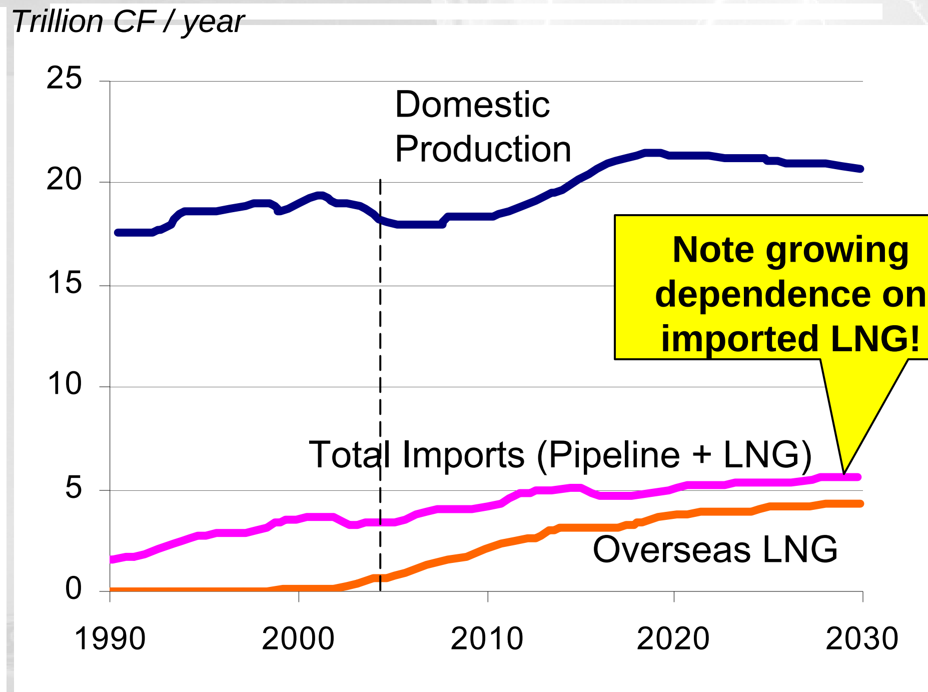
Energy Security Also Depends on Generating Mix

Switching from Imported Petroleum to imported Natural Gas does not enhance energy security:

– Generating source must be <u>domestic AND low-CO_2</u> .



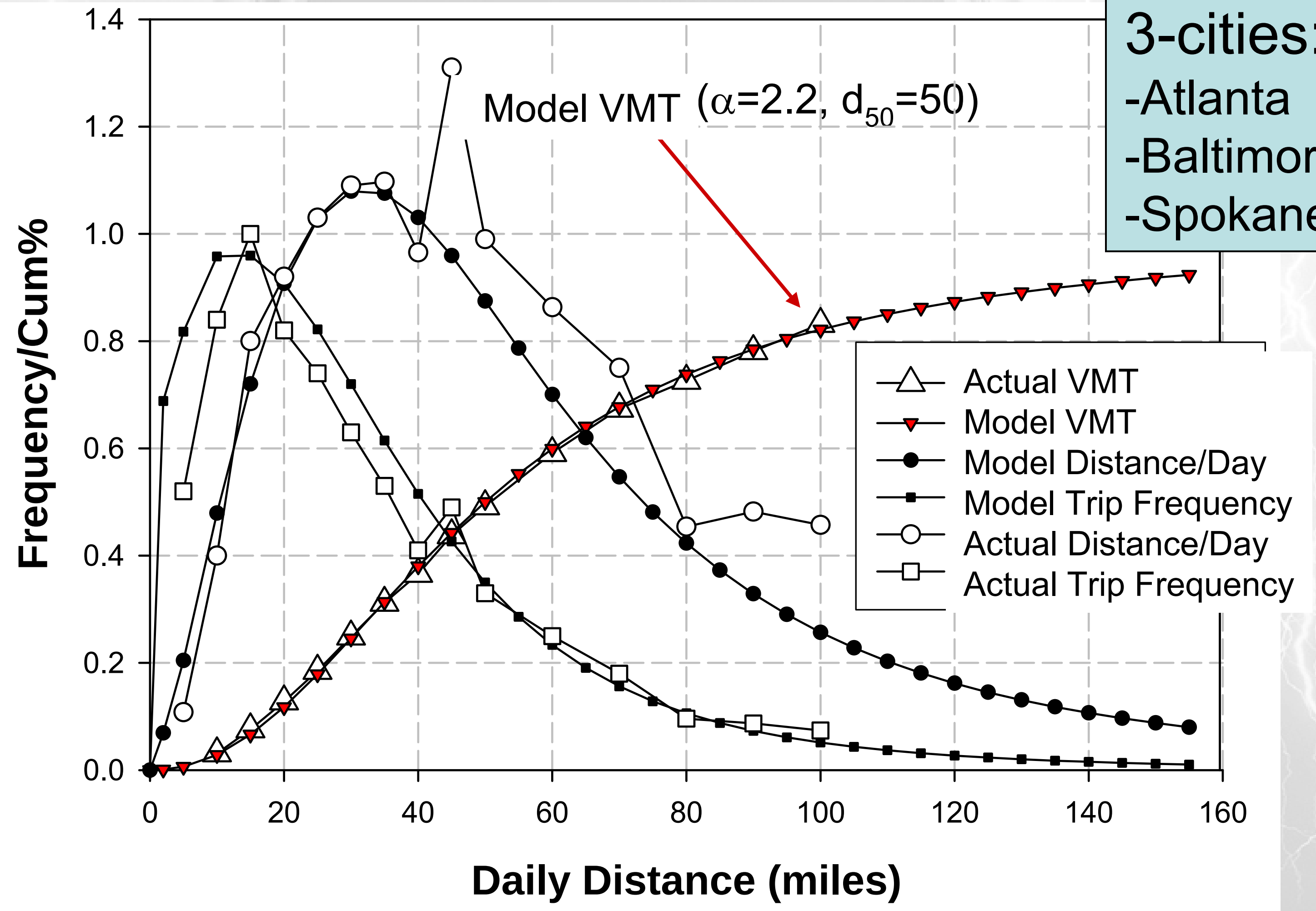
US Petroleum Production and Consumption



US Natural Gas Production and Imports

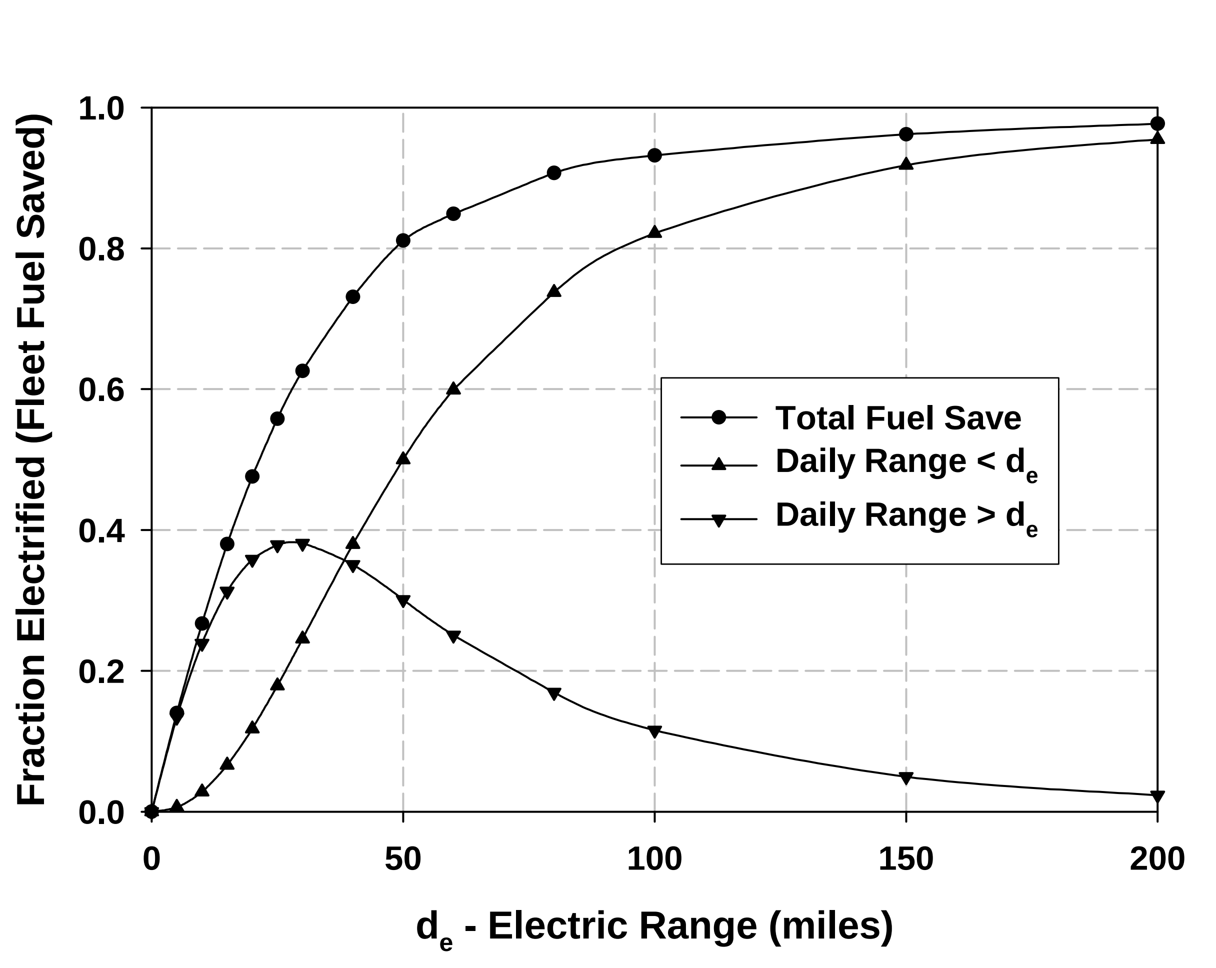
Sources: DOE/ORNL *Transportation Energy Data Book* (2004); EIA *Annual Energy Outlook 2006*.

Analytic Study of Real-World Vehicle Usage (example)



3-cities:
- -Atlanta
- -Baltimore
- -Spokane

Fuel Saving Potential of PHEV

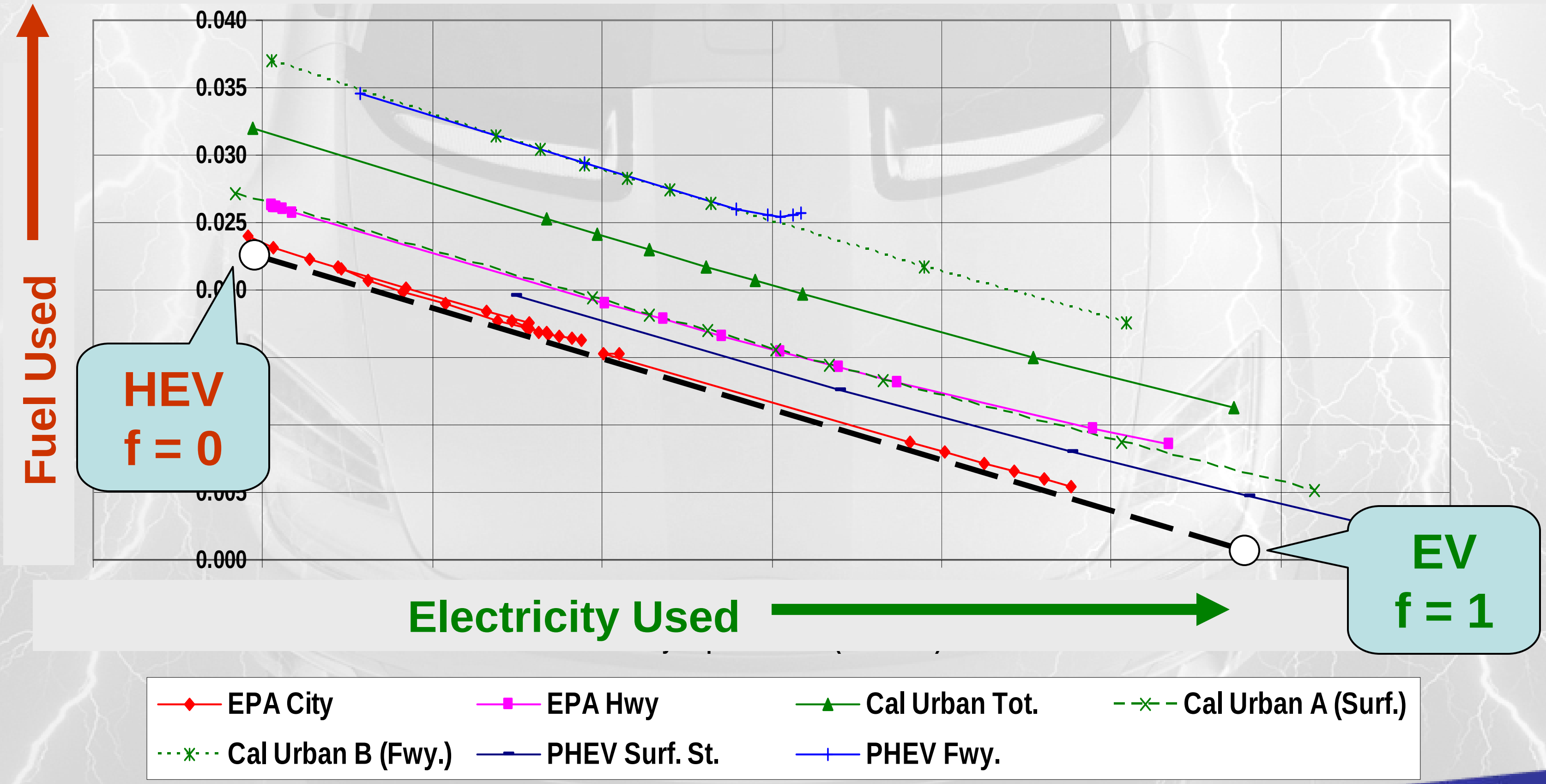


1. 30 miles "electric range" can displace over 60% of fleet fuel.
2. For modest e-range, fuel saving comes mainly from daily range less than the e-range!
3. For charge depleting (aka "blended") operation, fuel saving is reduced by the "electrification factor."

"Electrification Factor": f

For a Well-Optimized Full Hybrid, Fuel Saving is Strictly Linear with Electricity Usage:

- There is no optimal charge depletion strategy.
- We can choose "f" by design.



PI-HEV: Customer Cost/Benefit

- **AE driving appears cheap due to low electricity cost**
  - **~2 ¢/mile (@ 8 ¢/kWh) vs. 9 ¢/mile (gas @ $3/gal.)**
- But … this is not the complete story:
  - The battery cost is omitted: $5000*/60,000 mi** = 8 ¢/mile
    - *12 kWh battery; USABC long-range battery cost target
      - Includes incremental vehicle actions (wiring, cooling, structure, etc.)
    - **Assumes 50% AE operation and 8 year/120,000 mi battery (!)
  - **It will take a combination of battery cost breakthrough, stable electricity prices and extremely high gasoline prices to restore PI cost advantage, or …**
  - **Other stakeholders and beneficiaries (governments & utilities) must share the cost.**

PHEV Battery Requirements (adapted from USABC)

Power/Energy Ratio	5.4
Energy (nominal)	12 kWh (overnight charge @ 1.5 kW)
Power	65 kW
Cycle Avg. Efficiency	>90 % (round trip)
Cycle Life	300,000 (30-32% SOC) 5,000 (100-32-100% SOC)
Calendar Life	10 years, 150,000 miles*
Operating Temperature	-30 C to 50 C
USABC Target Price (100k/year)	$3400**

*For AT-PZEV credit, battery is warranted as part of emissions system

**Present cost is several times this target

Electric Vehicle; How Much is Too Much?

- Full-Function EV must eventually be compared to chemically-fuelled vehicle (ICE, FCV …)
  - Fuel System Requirements:
    - 400 miles range (130 kWh @ 0.33 kWh/mile)
    - < 200 kg system mass
    - < 10 minute refill time
  - Mass: Lightest proven chemistry is Li-ion
    - 130 kWh/3.5 V = 37 kAh = 1330 Moles of Li
    - "reactant mass" alone for $LiMnO_2$ - 6C system: 1330 x (3+55+32+72) = 215 kg (100% utilization)
      - No electrode, electrolyte, separator, tabs or enclosure!
  - Refill Time: 130 kWh/10 min. = 780 kW
    - 2000 Amp charge requires large cables & connectors
    - At 90% efficiency, station must extract 8 kW heat from the battery pack: connections for ~5 gal./min. of 10 C water.
    - Station capable of "fueling" 4 vehicles at once requires 2 MW service.
    - Even an 8 hour home charge would require 16 kW home service

EV Battery Requirements (adapted from USABC)

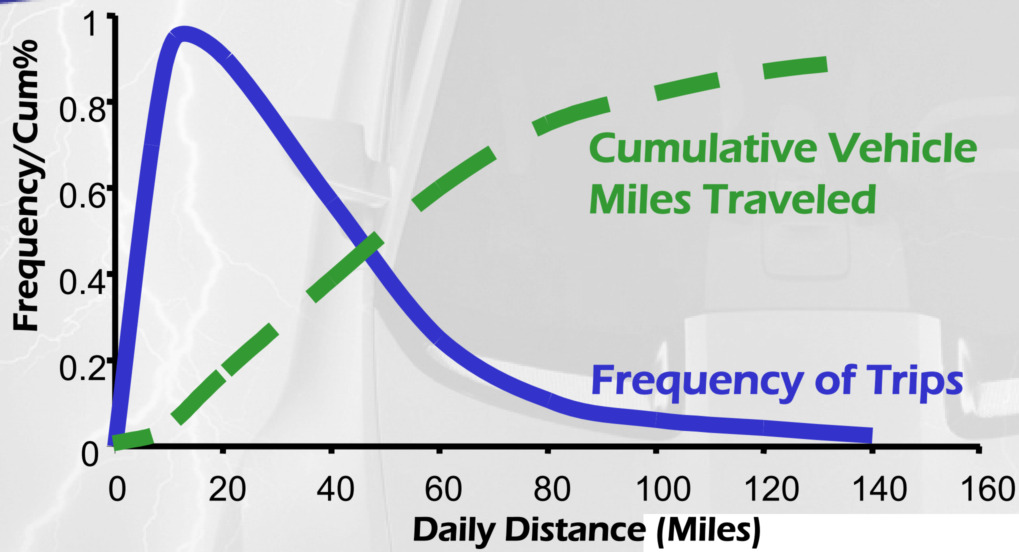
	Traditional EV	"Full Function" EV
Power/Energy Ratio	2.0 (~100 mile range)	0.9 (>300 mile range)
Energy (nominal)	40 kWh	130 kWh
Power	80 kW (modest performance)	120 kW (full performance)
Cycle Avg. Efficiency	>90 % (round trip)	>90% (round trip)
Cycle Life	1000 (100-20% SOC)	500 (100-20% SOC)*
Calendar Life	10 years, 100k miles	10 years, 150k miles
Operating Temperature	-30 C to 50 C	-30 C to 50 C
USABC Target Price (10k/year)	$6000** (150 $/kWh)	$12,000*** (100 $/kWh)

*Note that "full-function" battery is charged fewer times!

**Present cost several times this target

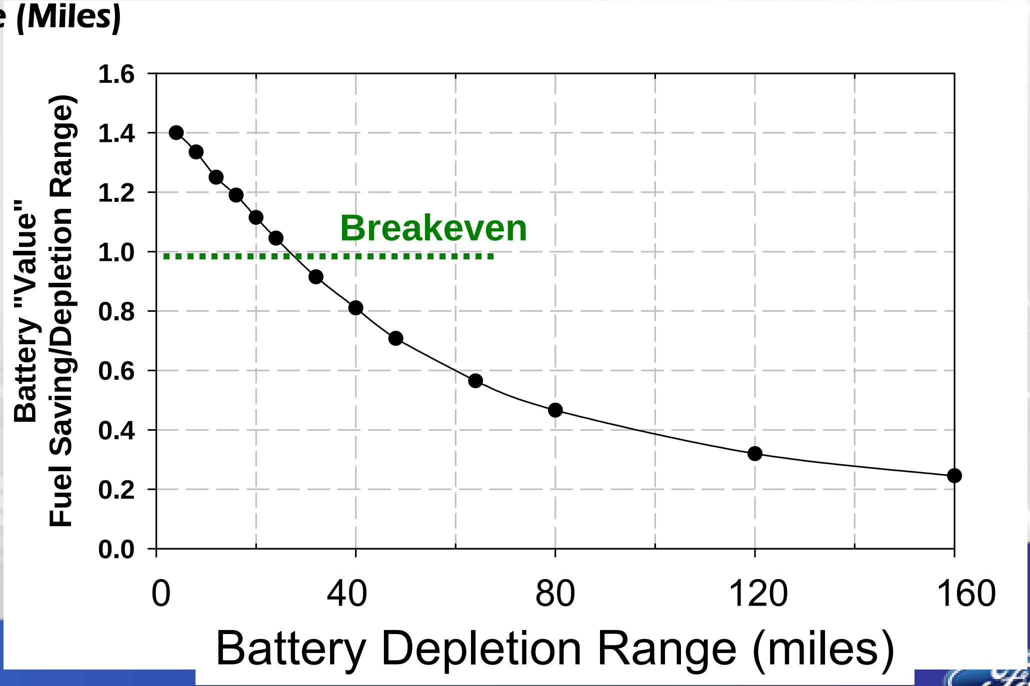
***This battery does not exist!

Battery Value: Fuel Savings vs. Battery Investment



- 30 miles EV range can "electrify" roughly 60% of all travel!
- Greater battery range is expensive and rarely used.

- To sustain breakeven, battery cost on $/kWh basis must drop with increasing range.
- Relative to 30 mile battery, 100 mile EV battery must be 2.5X cheaper and 400 mile battery must be ~10 X cheaper!

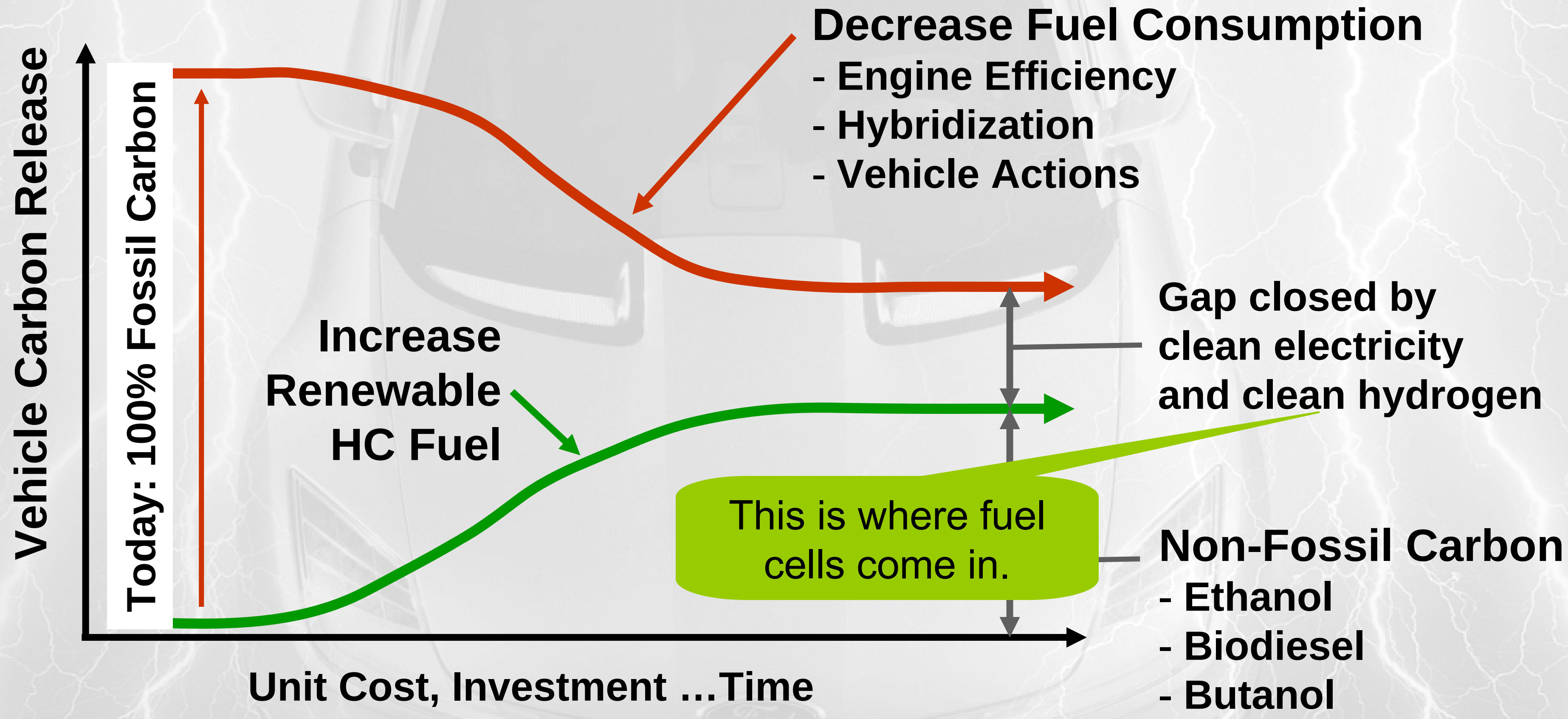


Battery Cost Recovery in Broad Application

	HEV	PHEV-30	Traditional EV	Full Function EV
Range	400	400	100	400
Energy (kWh)	2	12	40	120
Power (kW)	39	65	80	130
Power/Energy	20	5	2	1
USABC Cost Target	$800 ($400/kWh)	$3400 ($300/kWh)	$6000 ($150/kWh)	$12000 ($100/kWh)
Fuel Displacement	30%	70%	94%	100%
Battery "Value" $/fuel displaced*	26	48	64	120
Real Battery Cost Target	N.A.	$300/kWh	$113/kWh	$40/kWh

*Based on USABC targets.
Assumes zero incremental cost for other hybrid systems!

Path to CO_2-neutral Transportation



Can “electrification” close the gap between vehicle fuel need and renewable fuel availability?

MIT Study (Groode and Heywood)

Fuel crops can provide significant fraction of vehicle fuel.

	2006	2025		
Feedstock	**Iowa Corn Kernel**	**Iowa Corn Kernel**	**Iowa Corn Kernel + Corn Stover**	**Switchgrass**
Ethanol Production	18 Billion Liters (4.8 Billion Gallons)	130 Billion Liters (35 Billion Gallons)		
% of US Gasoline Consumption	2.3% of 2006 Consumption	12% of 2006 Consumption		
% of US GHG Emissions Displaced (w/out credit)	0% (w/out credit)	3.3%	6%	12%
% of US 2006 Corn Cropland	20.4%	75%	60%	50%
% of 2006 US Cropland	3.6%	14%	11%	10%

US DoE "Billion-Ton Study"

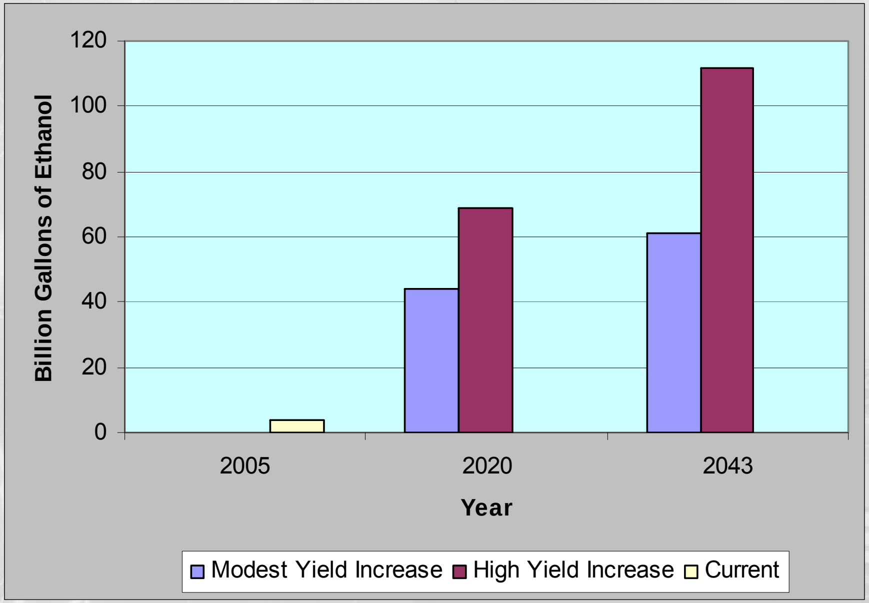
Assumptions:

-No increase in total US acreage under cultivation (450 million acres)

-Rebalance production between food and fuel crops

-Cellulosic ethanol production from fuel crop, other agricultural waste, forestry and wood byproducts.

Conclusion: A significant fraction of transportation fuel *can* be displaced by bio-ethanol.



Dependent on:

1. Improvement in crop yields
2. Increase in lignocellulose feeds
3. Improvement in lignocellulose to ethanol process yields

Gasoline consumption:

1. For 2020, 173 billion gallons (EIA)
2. For 2050, 222 billion gallons (scaled with population)

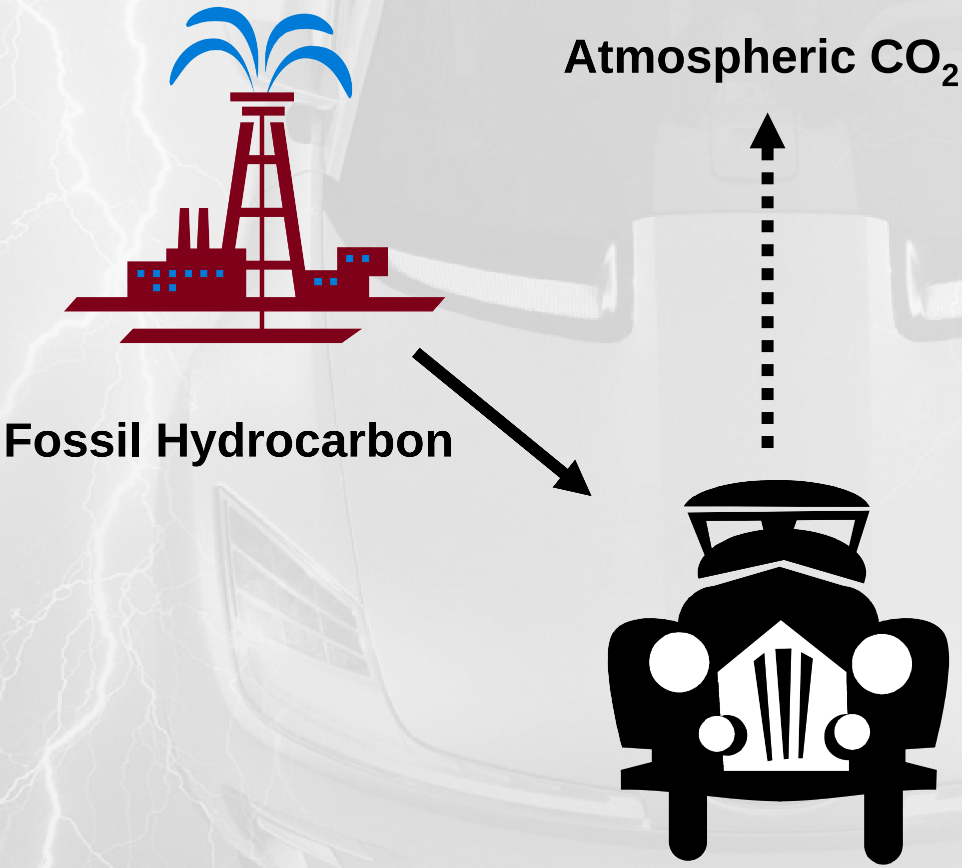
Conclusions: The "Big Picture"

- Batteries may be central to sustainable personal transportation on a national basis.
  - Increasing powertrain efficiency (HEV)
  - Displacing chemical fuel (PHEV, EV)
- Cost reduction and domestic supply are critical.
- Fuel displacement is not linear with battery capacity.
  - High-capacity applications will come last.
- Plug-In Hybrid has the potential to close the gap between transportation fuel need and renewable fuel availability.
  - PHEV creates new economic relationship between stationary and mobile energy industries.

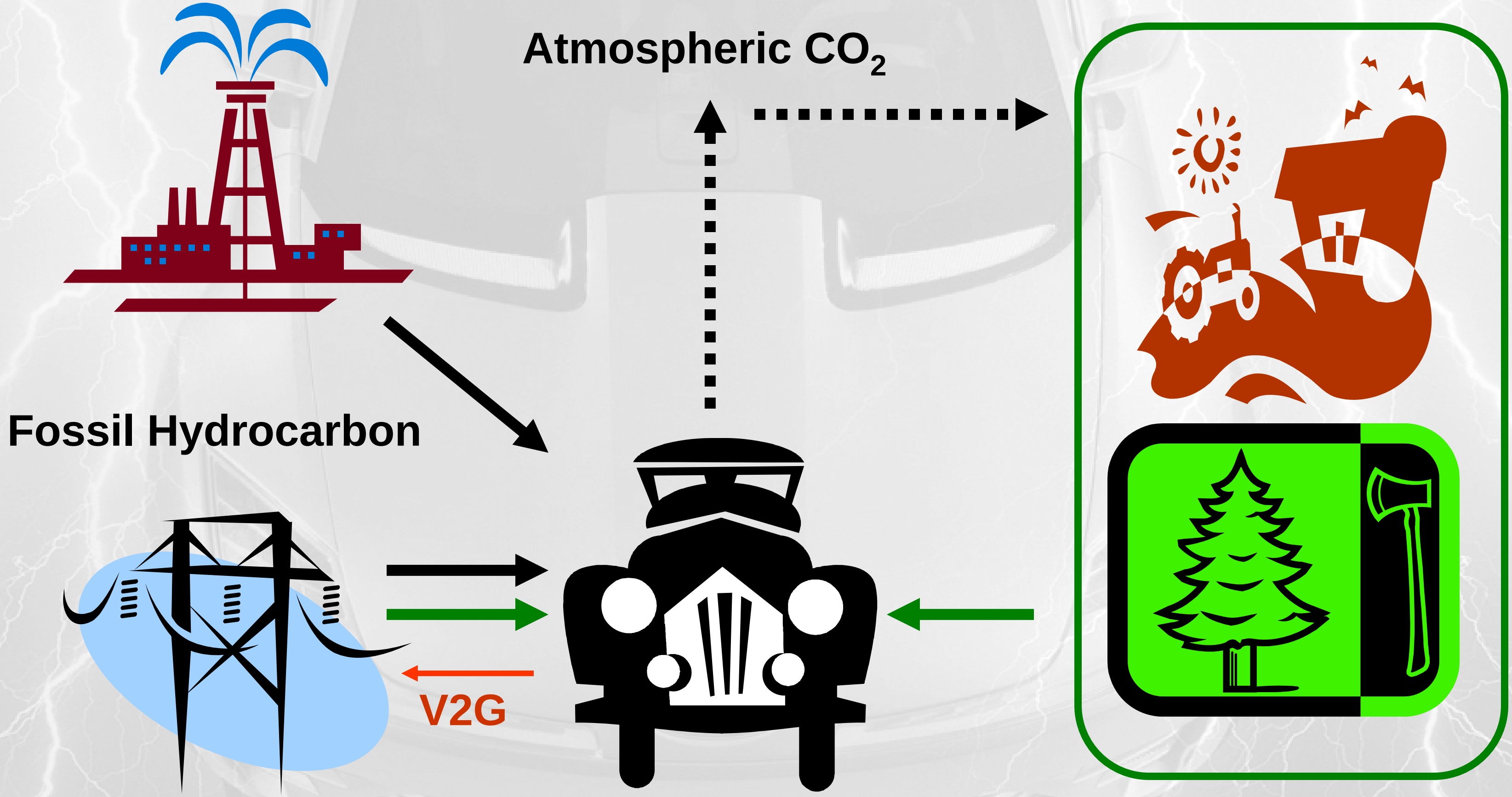
The Road to Sustainable Mobility

- To have truly global impact, vehicle efficiency and sustainable fuel technologies must be deployed on a massive scale.
  - Niches and a few percent here and there won't do the job.
- The keys to mass acceptance of high-efficiency and renewable fuel technologies are suitability to customer needs and affordable cost –
  - i.e customers must be willing and able to pay for new technology
- Improvements in vehicle efficiency do reduce demand for fuel, including renewables. However, even with greatly improved vehicle efficiency, production of sufficient renewable fuels will require huge investments in new infrastructure, production and delivery facilities … and a workable business equation.
- Success in this endeavor requires both elements, and depends on new levels of cooperation, and <u>new relationships</u> between all stakeholders.

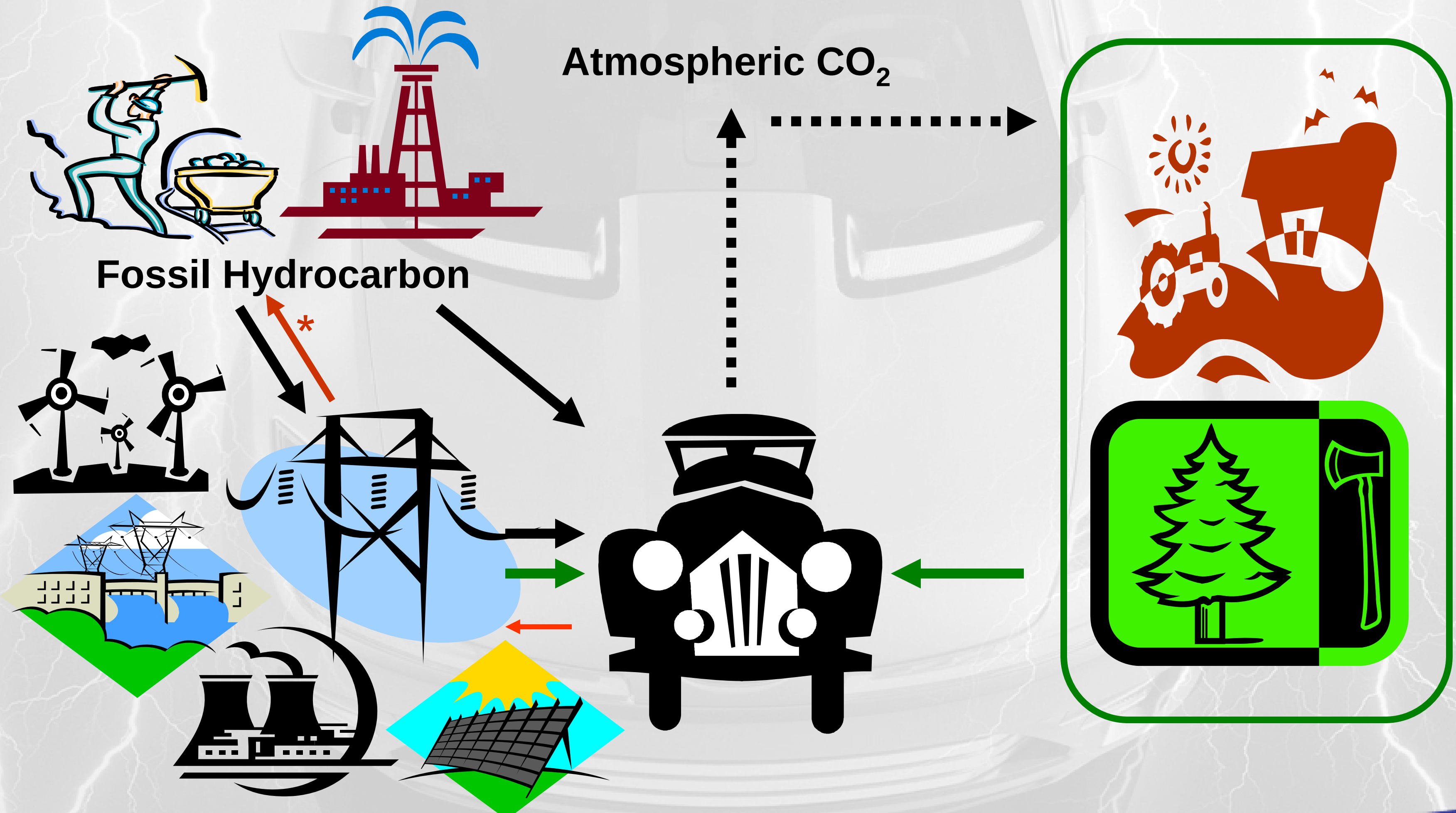
The Old Transportation Economy



The New Transportation Economy



The New Transportation Economy



*CO2 sequestration?

Thank You!