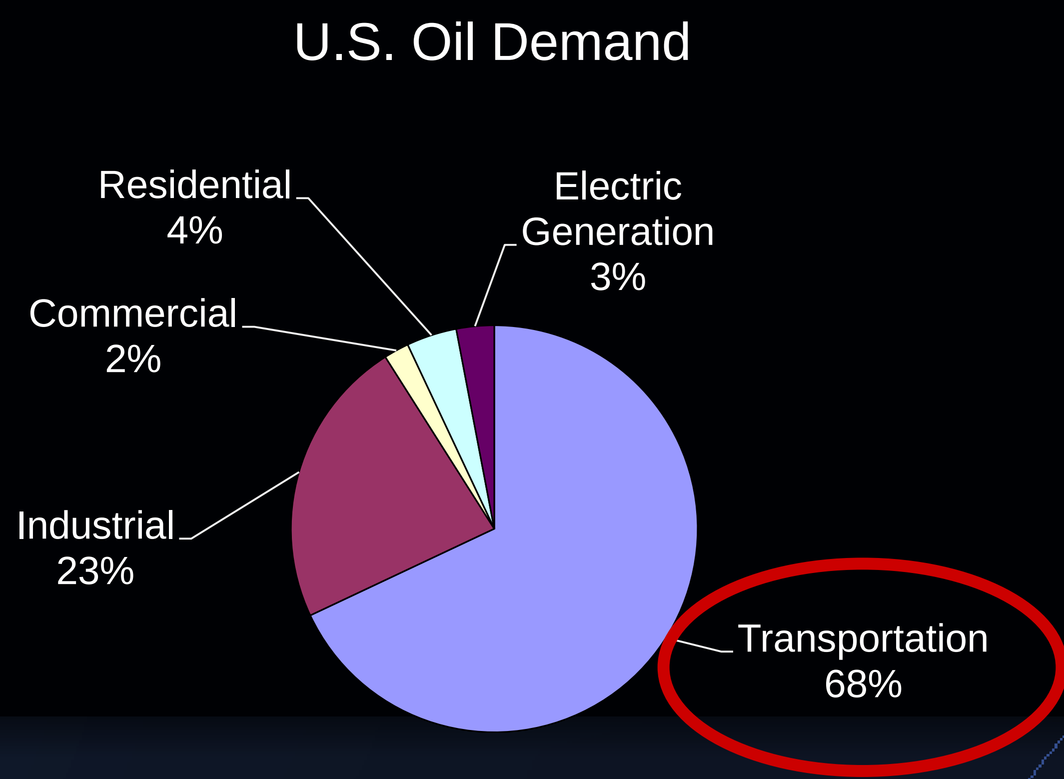
Electric Future

Martin Eberhard

Topics

- The Problem
- Why EVs Make Sense
- Electric Vehicle Infancy
- An Engineering Example
- Technology Heads-Up

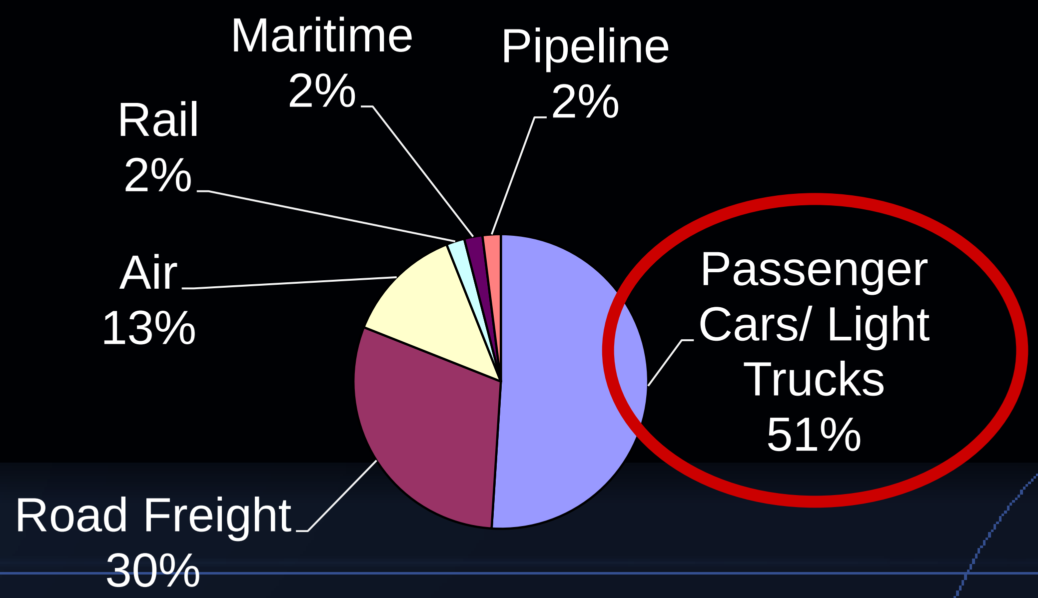
The Problem



Source: Annual Energy Outlook 2003, Energy Information Administration, U.S. Department of Energy

The Problem

Oil for Transportation



The Problem

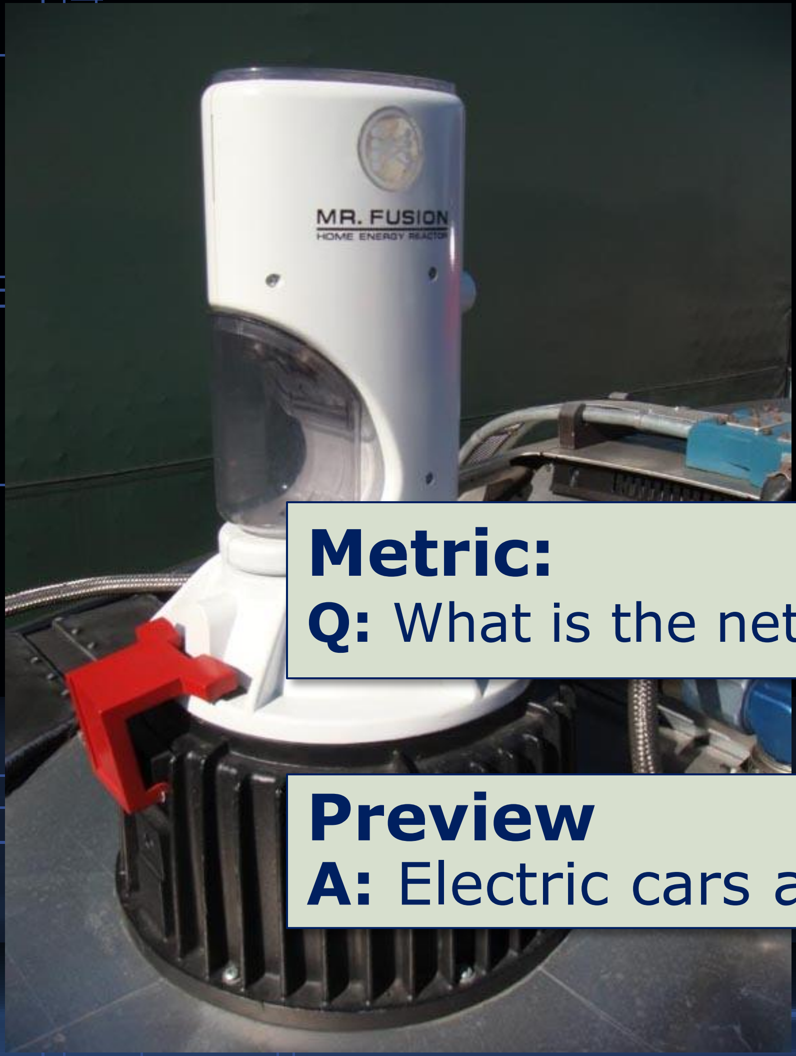
500 Million cars worldwide in 1986

950 Million cars today

2.4 **Billion** cars by 2050

Can we really power them all with petroleum?

If not oil, then what?



- Battery-electric?
- Biodiesel?
- Clean diesel?
- Ethanol?
- Hybrid?
- Hydrogen fuel cells?
- Mr. Fusion?

Metric:

Q: What is the net resource consumption per mile?

Preview

A: Electric cars are by far the best choice

Why EVs Make Sense

Don’t EVs just move the problem upstream?

Well-to-Wheel Energy Analysis

Pretty Good Gasoline Car: 26 MPG

Production Efficiency	Gasoline Energy Content	Vehicle Mileage		Well-to-Wheel Energy Consumption
81.7%	36066 Wh/gal	26 MPG	→	1697 Wh/mi

Best Case Gasoline Car: 41 MPG

Production Efficiency	Gasoline Energy Content	Vehicle Mileage		Well-to-Wheel Energy Consumption
81.7%	36066 Wh/gal	41 MPG	→	1077Wh/mi

Fuel energy content: *Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle, 29 October 2003, Ulf Bossel*
Vehicle mileage: US EPA   www.fueleconomy.gov
Production Efficiency: *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis, June 2001, by General Motors Corporation, Argonne National Laboratory, BP, ExxonMobil, and Shell*

Well-to-Wheel Energy Analysis

High Performance Electric Car: 150 Wh/km
Legacy Coal Electric Production

Coal Plant Net Energy Ratio	US Electric Grid Efficiency	Charging Efficiency	Vehicle Mileage		Well-to-Wheel Energy Consumption
29%	92%	90%	250 Wh/mi	→	1041 Wh/mi

Coal net energy ratio: ***Life Cycle Assessment of Coal-fired Power Production by*** Pamela L. Spath, Margaret K. Mann, Dawn R. Kerr, page 41

Well-to-Wheel Energy Analysis

High Performance Electric Car: 150 Wh/km

State-of-the-Art Coal Electric Production

Recovery, Processing, Transport Efficiency	Electric Generation Efficiency	US Electric Grid Efficiency	Charging Efficiency	Vehicle Mileage		Well-to-Wheel Energy Consumption
85%	**45%**	**92%**	**90%**	**250 Wh.mi**	→	**789 Wh/mi**

At 45% efficiency, the Isogo Power Plant in Japan is among the most efficient coal-fired generators in the world.

Coal net energy ratio: ***Life Cycle Assessment of Coal-fired Power Production by*** Pamela L. Spath, Margaret K. Mann, Dawn R. Kerr, page 41

Well-to-Wheel Energy Analysis

High Performance Electric Car: 150 Wh/km
State-of-the-Art Natural Gas Electric Production

Recovery, Processing, Transport Efficiency
95%

Electric Generation Efficiency
60%

US Electric Grid Efficiency
92%

Charging Efficiency
90%

Vehicle Mileage
250 Wh/mi

Well-to-Wheel Energy Consumption
530 Wh/mi

GE Energy

"GE's H System is an advanced combined cycle system capable of breaking the 60 percent efficiency barrier integrating the gas turbine, steam turbine, generator and heat recovery steam generator into a seamless system."

Production efficiency and electric grid efficiency: *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels – North American Analysis, June 2001, by General Motors Corp., Argonne National Laboratory, BP, ExxonMobil, and Shell*

Well-to-Wheel Energy Analysis

Pretty Good Gasoline

1697 Wh/mi

Best Available Gasoline

1077 Wh/mi

Legacy Coal

1041 Wh/mi

Best Realistic Case Coal

789 Wh/mi

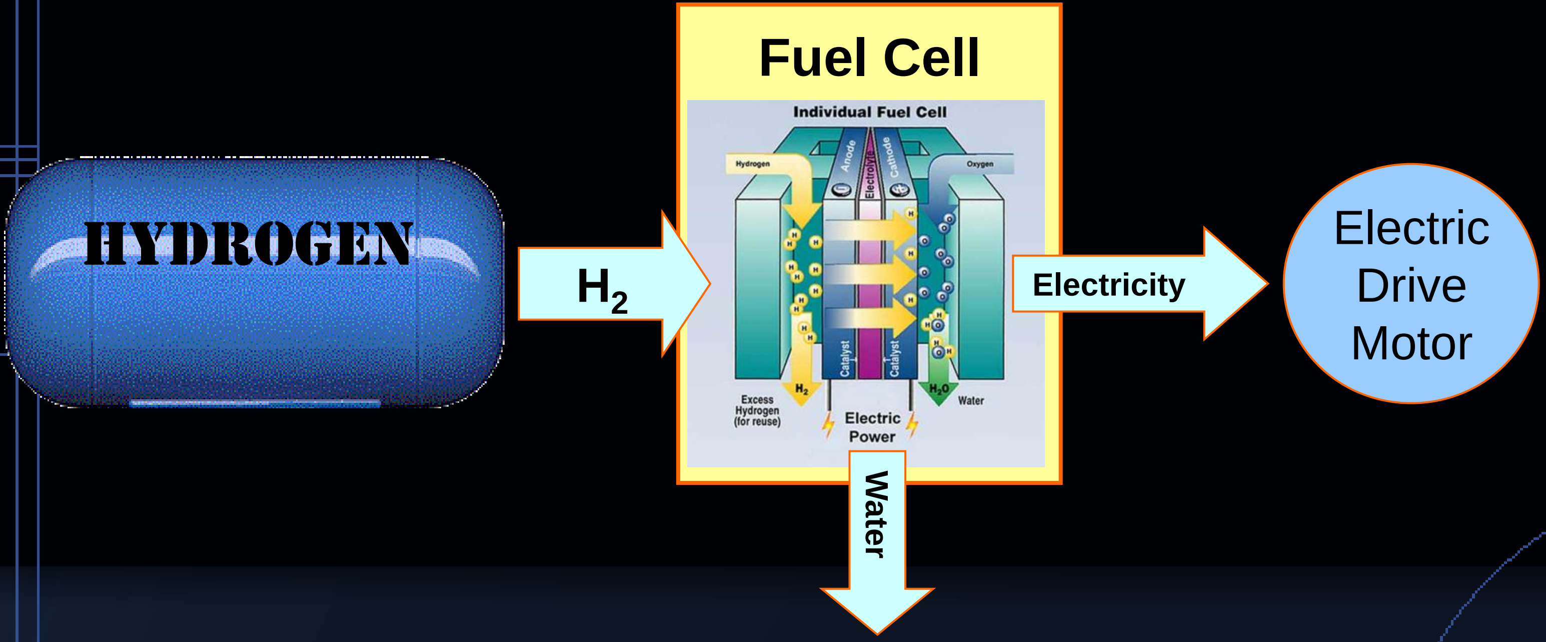
Best Case Natural Gas

530 Wh/mi

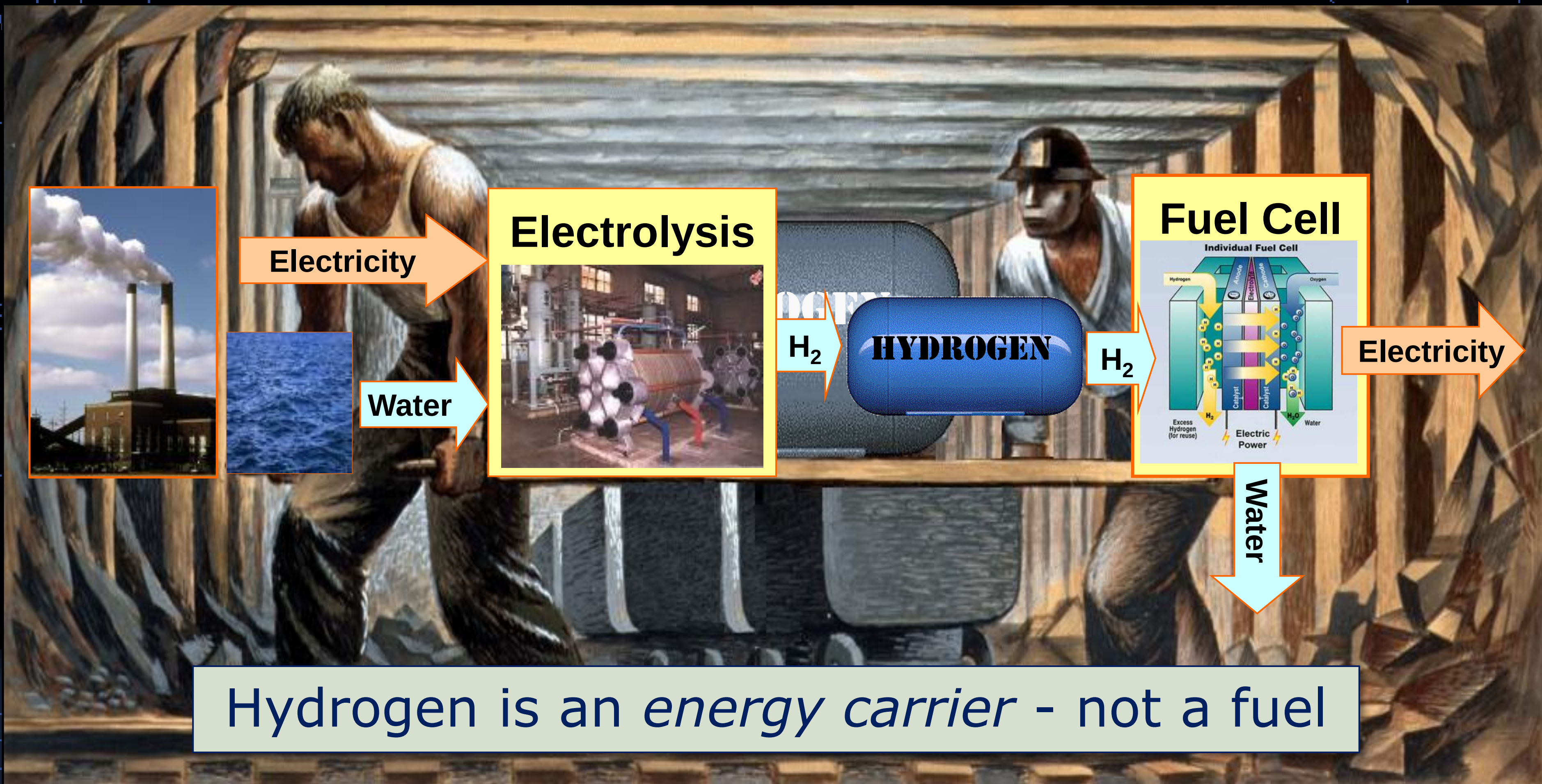
Note: you don't need these fossil fuels for EVs

Are EVs more efficient than other “green” cars?

What about Hydrogen Fuel Cells?



Where does hydrogen come from?



Hydrogen is an *energy carrier* - not a fuel

What about Hydrogen Fuel Cells?

Q: How far will one unit of electricity power a car?

Photovoltaic

Wind Turbine

Hydroelectric

Geothermal

Electricity →

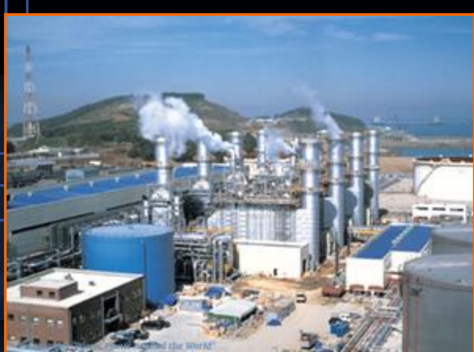
Electric Energy Storage

Storage efficiency = $\dfrac{\textbf{Electricity in}}{\textbf{Electricity out}}$

Electricity →

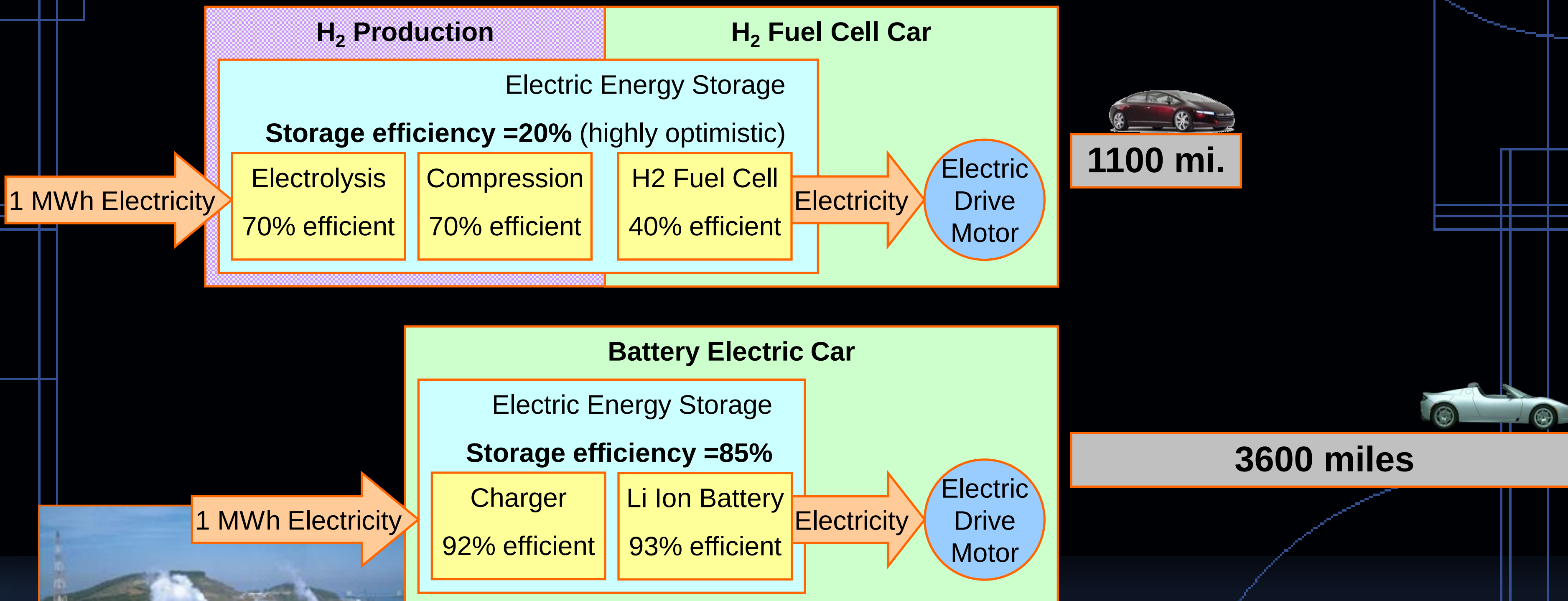
Electric Drive Motor

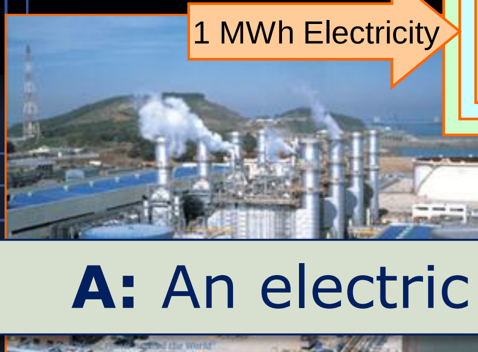
X miles



What about Hydrogen Fuel Cells?

Q: How far will one unit of electricity power a car?





A: An electric car will go 3 times as far as a fuel cell car

What about Ethanol?

Q: How far will one unit of biomass power a car?

biomass

Energy Conversion

Car

Energy Conversion

Biomass efficiency = $\dfrac{\textbf{miles driven}}{\textbf{Ton of biomass}}$

X miles

What about Ethanol?

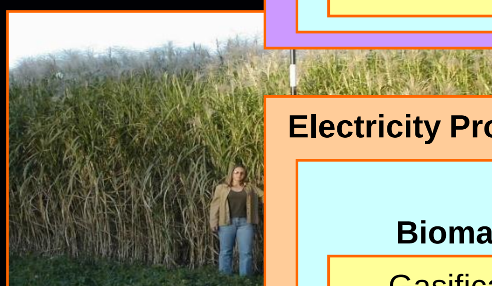
Silly Q: How far will one unit of biomass power a car?

Ethanol Production | **Ethanol ICE Car**

Energy Conversion (highly optimistic)

Biomass efficiency = 2200 miles / ton

1 ton of biomass → Best-case Ethanol Production, 50 GGE / ton[1] → IC Engine, 45 miles per gallon → **2200 miles**



Electricity Production | **Electric Car**

Energy Conversion

Biomass efficiency = 3600 miles / ton

1 ton of biomass → Gasification Combined Cycle Electric Generation, 1000 kWh / ton[2] → Electric car, 3.6 miles / kWh → **3600 miles**

A: An electric car will go 60% farther than an ethanol car

1. Iogen enzymatic process, gallons of gasoline equivalent
2. Southern Company Services

What about Ethanol?

Better Q: How far will an acre of land power a car per year?

land	→	**Fuel Production** / **Car** Energy Conversion **land efficiency** = $\dfrac{\textbf{miles driven}}{\textbf{acre of land per year}}$	→	**X miles/year**

What about Ethanol?

Better Q: How far will an acre of land power a car per year?

Ethanol Production

Ethanol ICE Car

Energy Conversion (highly optimistic)
efficiency = 11,000 miles per acre per year

1 acre of farmland

Corn Farming
125 bu/ acre per year[1]

Ethanol Production
1.94 GGE / bu[2]

IC Engine
45 miles per gallon

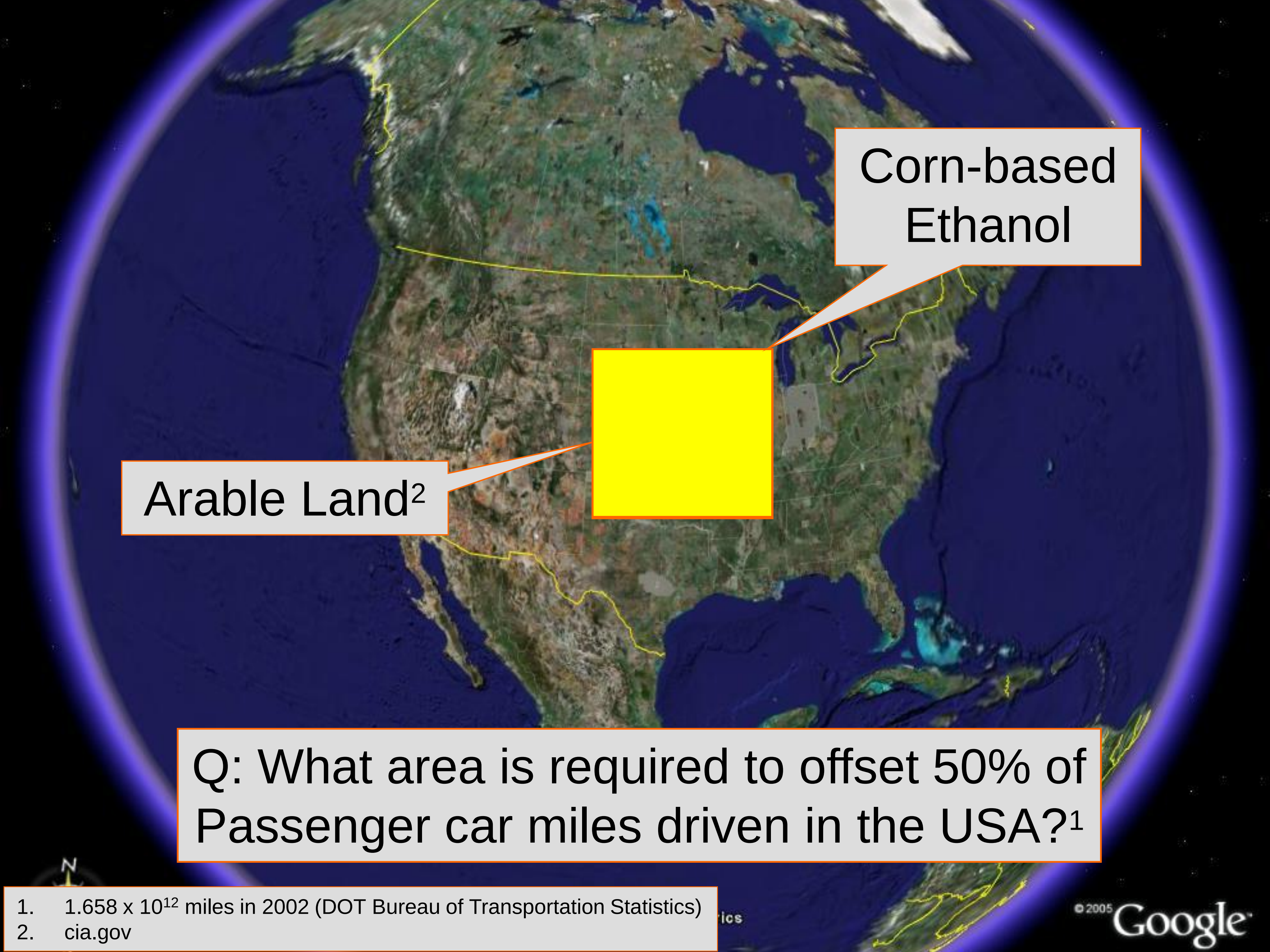
~~**11K miles**~~

2,100 miles

Energy input[1]
1.91 GGE/BU

Co-product credit[1]
0.35 GGE/BU

1. Estimating the Net Energy Balance of Corn Ethanol, Shapouri, et al, USDA, 1995
2. 2.7 gal ethanol/bu / 1.39 gal ethanol/gge



Q: What area is required to offset 50% of Passenger car miles driven in the USA?[1]

1. 1.658×10^{12} miles in 2002 (DOT Bureau of Transportation Statistics)
2. cia.gov

What about Ethanol?

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Ethanol Production

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How about Cellulosic Ethanol?

Better Q: How far will an acre of land power a car per year?

Cellulosic Ethanol Production | **Ethanol ICE Car**

Energy Conversion (highly optimistic)
efficiency = 52,000 miles per acre per year

Energy input[1] ~7 GGE/ton → 1 acre of farmland →

- Miscanthus Farming: 15 tons / acre per year[1]
- Enzymatic Ethanol Production: 50 GGE / ton[2]
- IC Engine: 45 miles per gallon

→ ~~52K miles~~ **46K miles**

Electricity Production | **Electric Car**

Energy Conversion
efficiency = 1.6M miles per acre per year

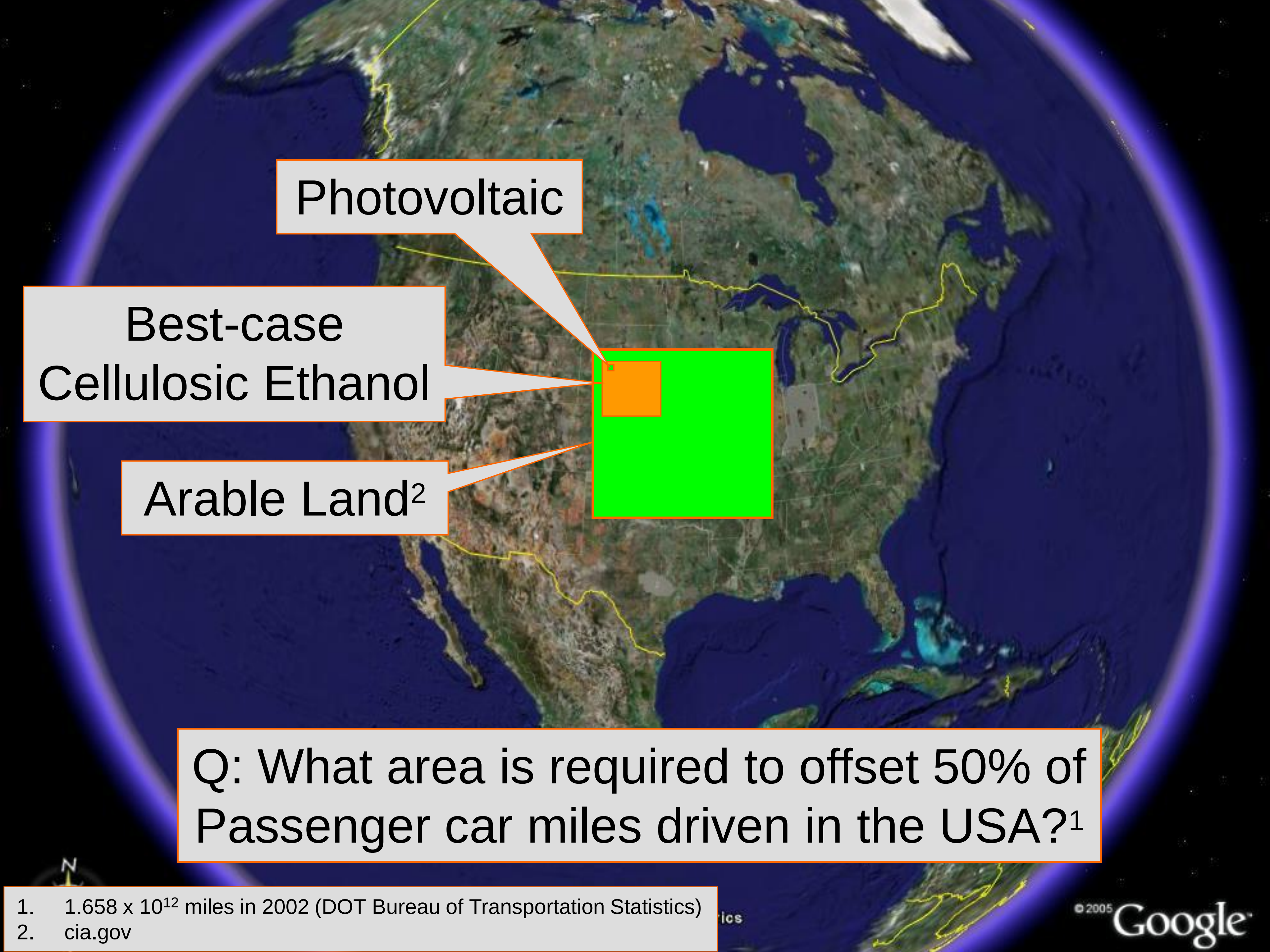
1 acre of *desert* land →

- Solar Thermal Installation: 446 MWh / acre[3] per year
- Electric car: 3600 miles / MWh

→ **1600K miles**

A: An electric car will go **35 times** as far as an ethanol car

1. Dr. Madhu Khana, University of Illinois
2. Iogen enzymatic process, gallons of gasoline equivalent
3. Wikipedia: Nevada Solar One: 300 acres of collectors, 134,000 MWh/year



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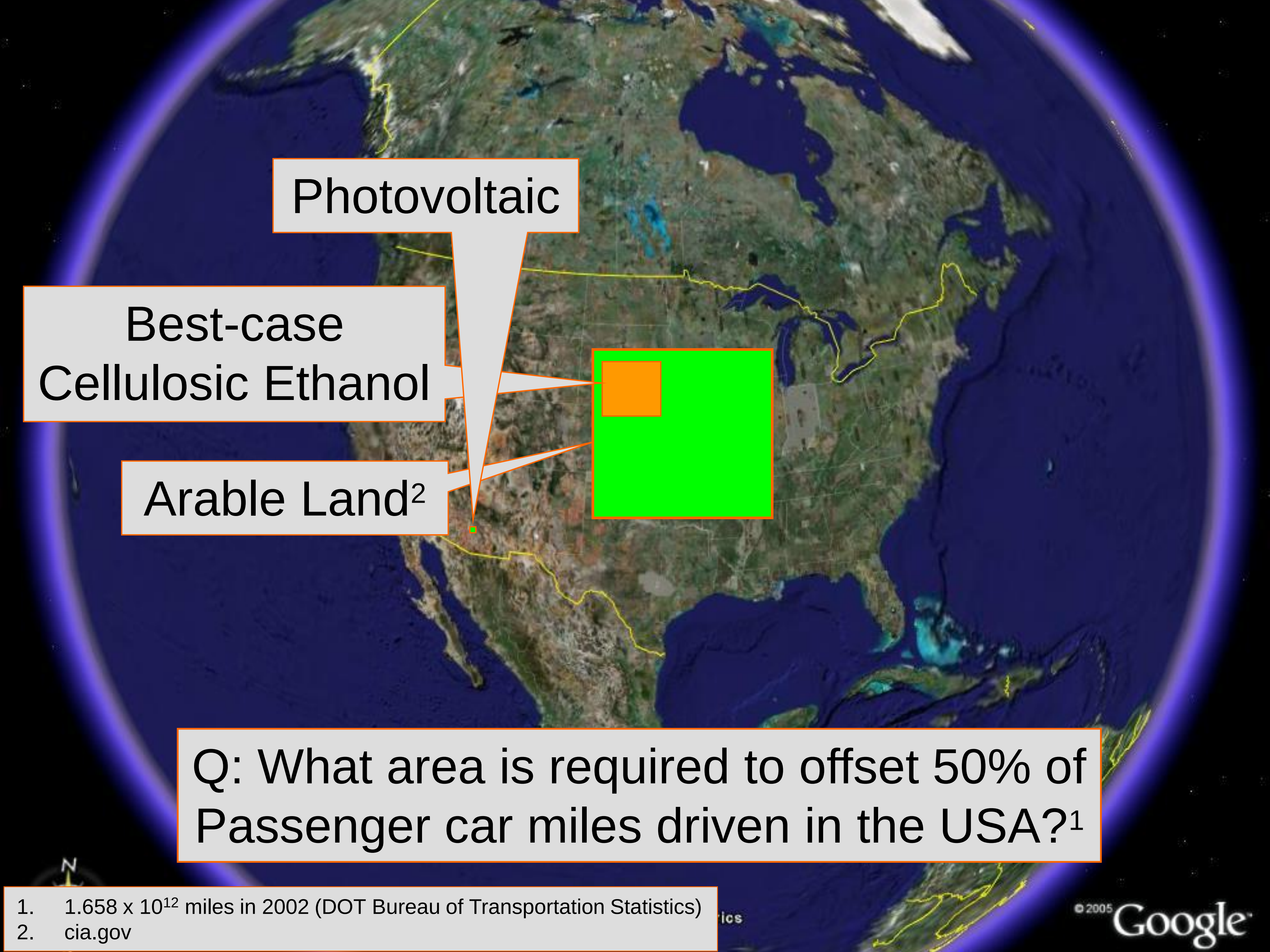

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1. 1.658×10^{12} miles in 2002 (DOT Bureau of Transportation Statistics)
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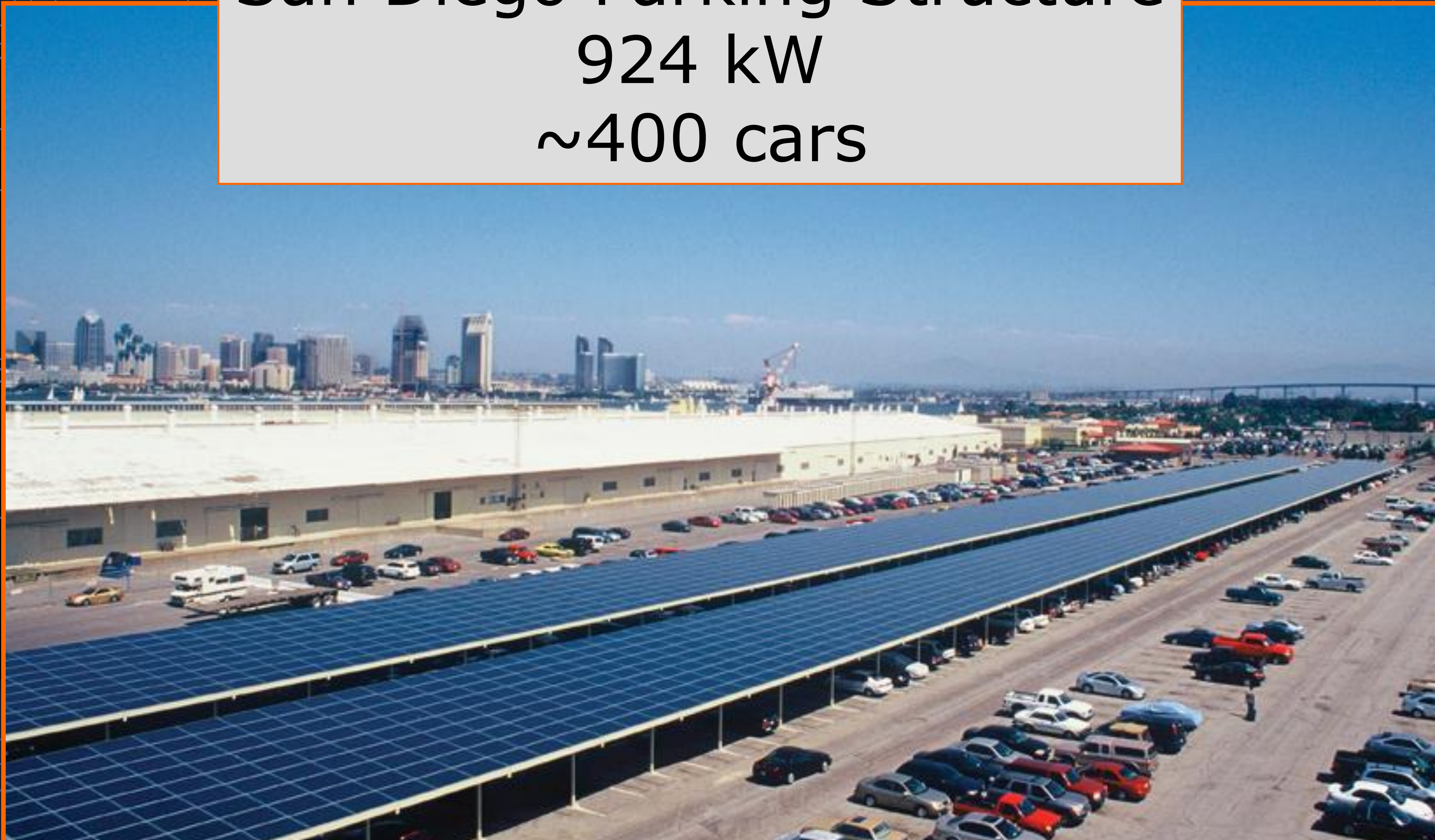
California Desert Solar Thermal
354 MW
~230,000 cars

California Desert Solar Thermal (under construction) 553 MW ~360,000 cars

German Photovoltaic
10 MW
~4,000 cars

San Diego Parking Structure
924 kW
~400 cars



WalMart Rooftop
605 kW
~260 cars

Silicon Valley Parking Lot
205 kW
~ 90 cars

Individual Choice
3 kW
1 car

Martin’s House
5.2 kW
1 fast car

What about Diesel (Bio or Otherwise)?

Q: How many miles will one gallon of diesel power a car?

(Bio)diesel → Energy Conversion

efficiency = <u>miles driven</u>
Gallon of biodiesel

→ **X miles**

What about Diesel (Bio or Otherwise)?

Q: How many miles will one gallon of diesel power a car?

Diesel Car

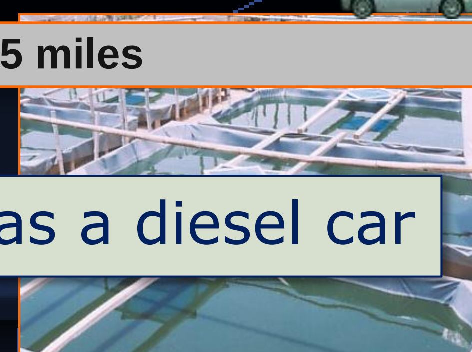
Energy Conversion
efficiency = 38 miles per gallon

1 gallon (bio)diesel → Diesel Engine[1] 38 miles per gallon → **38 miles**

Electricity Production | **Electric Car**

Energy Conversion
efficiency = 65 miles per gallon

1 gallon (bio)diesel → Diesel generator 18.21 kWh per gal[2] → Electric car 3.6 miles per kWh → **65 miles**



A: An electric car will go about twice as far as a diesel car

1. 2006 VW Diesel Beetle (EPA)
2. e.g. Anguilla Electric Company, 2001 average

If not oil, then what?

- Battery-electric?
- Biodiesel?
- Clean diesel?
- Ethanol?
- Hybrid?
- Hydrogen fuel cells?
- Mr. Fusion?

As I said…
A: Electric cars are by far the best choice

Electric Vehicle Infancy

Baby steps so far

Electric Vehicle Infancy

Of course, early EVs will have some missteps

Electric Vehicle Infancy

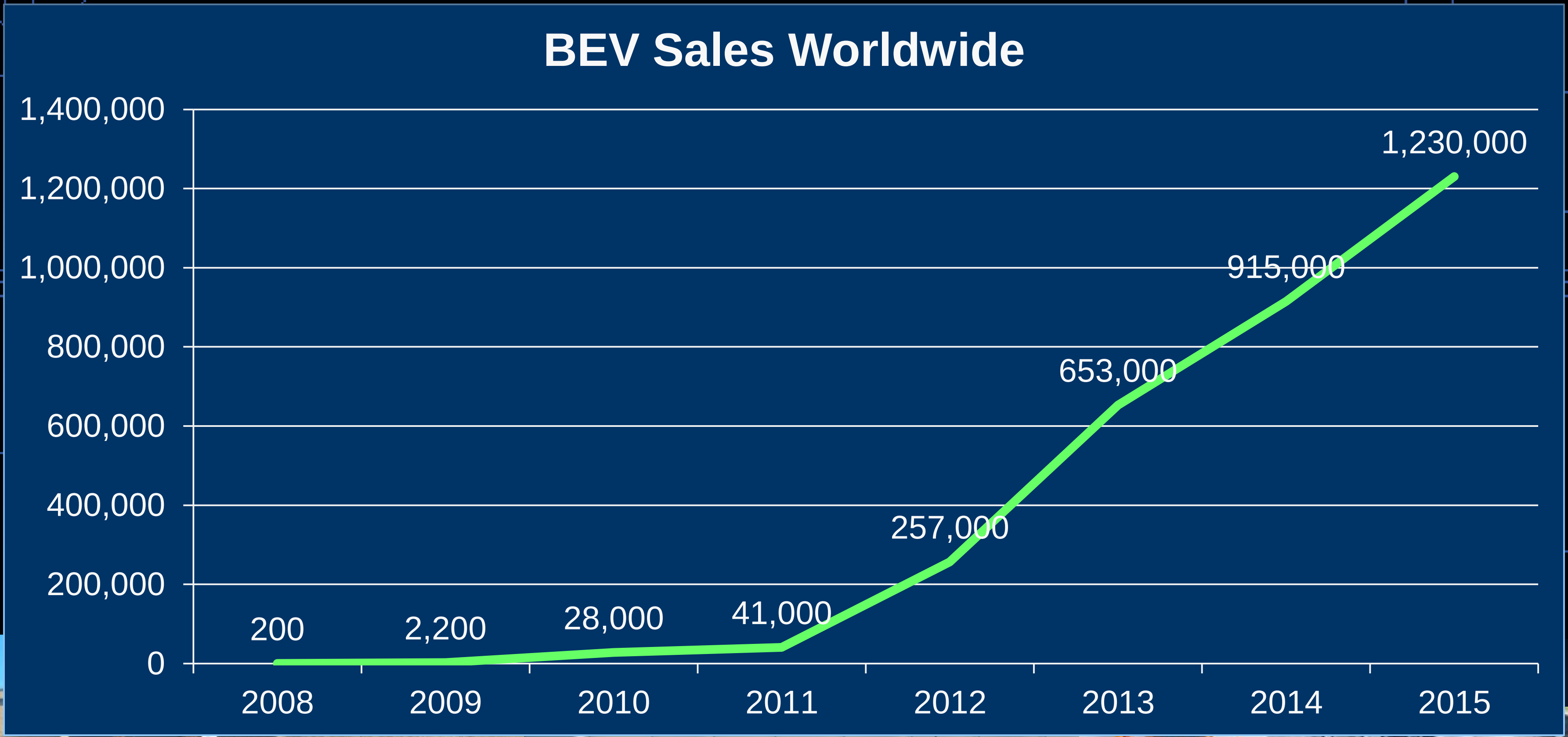
And.. not every EV will be a success

Electric Vehicle Infancy

But... every car company is launching EVs

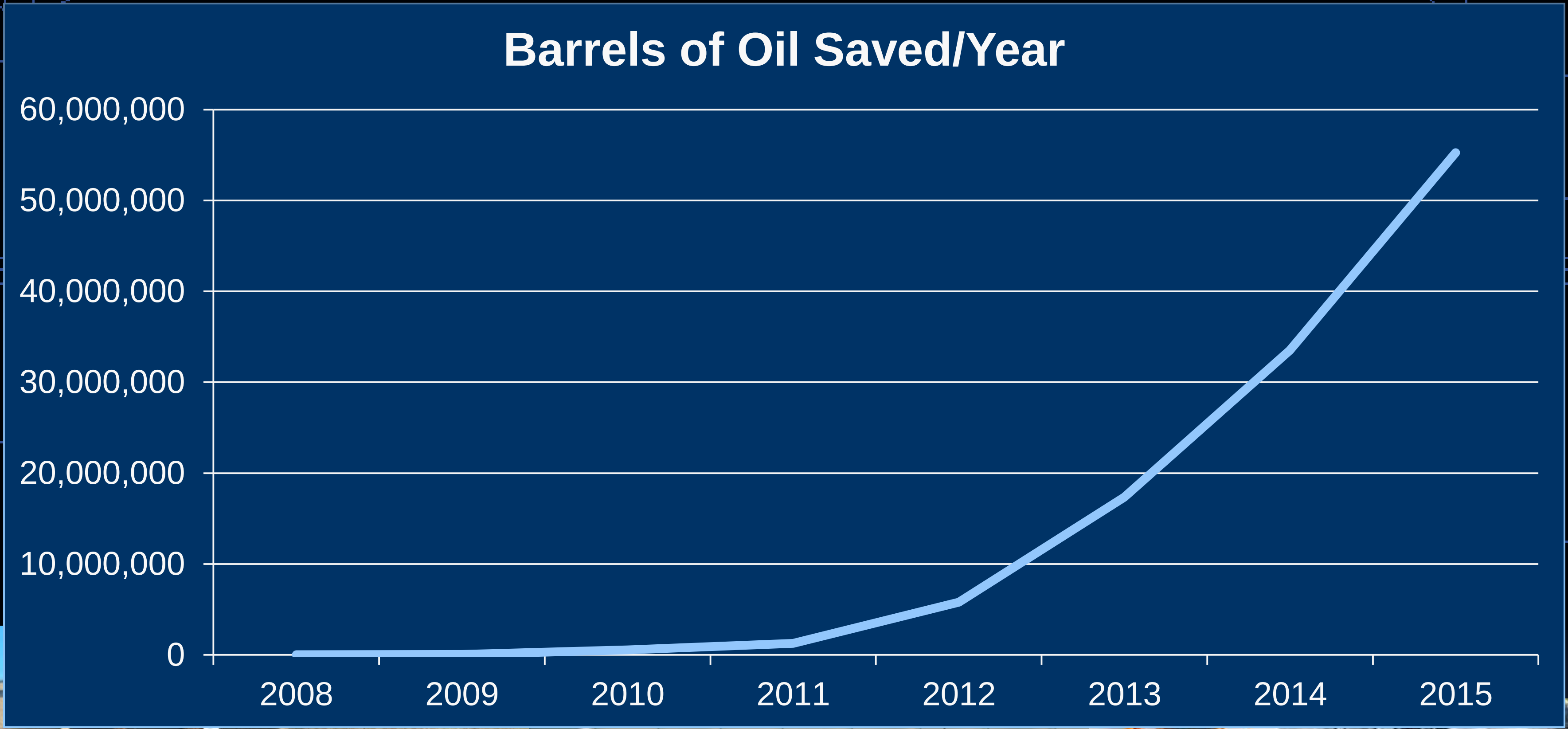
Electric Vehicle Infancy

And the numbers are beginning to add up



Electric Vehicle Infancy

And the numbers are beginning to add up



An Engineering Example: Battery System Safety

Assumption:

Commodity cells are not safe enough for cars (or planes)

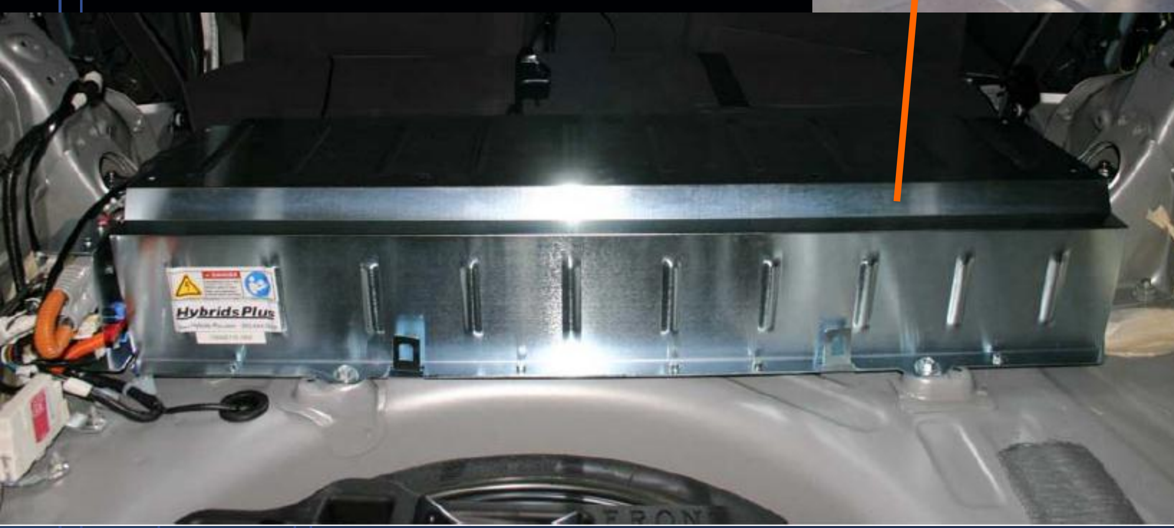
Lesson:
Safety is a System Design Issue

Instructive Example

Plug-in Hybrid conversion with A123 (LiFePo) cells

A123-based conversion battery pack

"Safe" LiFePo Cells inside



Instructive Example

Connection failure caused by incorrect installation

Instructive Example

Fire propagated through "safe" LiFePo battery pack

"Report of Investigation: Hybrids Plus Plug In hybrid Electric Vehicle Prepared for National Rural Electric Cooperative Association, inc. and U.S. Dept. of Energy, Idaho National Laboratory by ETEC" June 26, 2008, by Garrett P. Beauregard

Instructive Example

Full vehicle fire caused by "safe" LiFePo battery pack

Rapid Corrosion

For <u>any</u> type of cell, for any battery system

- <u>All</u> energy cells have a non-zero chance of runaway
- Thermal runaway is less likely with some cells than others
- Unless the chance is ZERO, we must <u>prevent propagation</u>
- i.e. energy released by any cell *must not* ignite neighbors

- This is a *system design* issue:
  - Minimize energy released
  - Absorb energy
  - Engineered cell spacing
  - Ensure adjacent cells are not overcharged
  - Shield and deflect heat

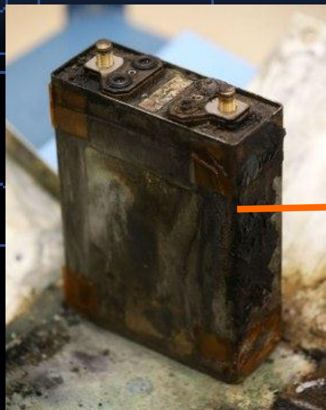
Fact: small cells release less energy

A safe pack is easier with small cells

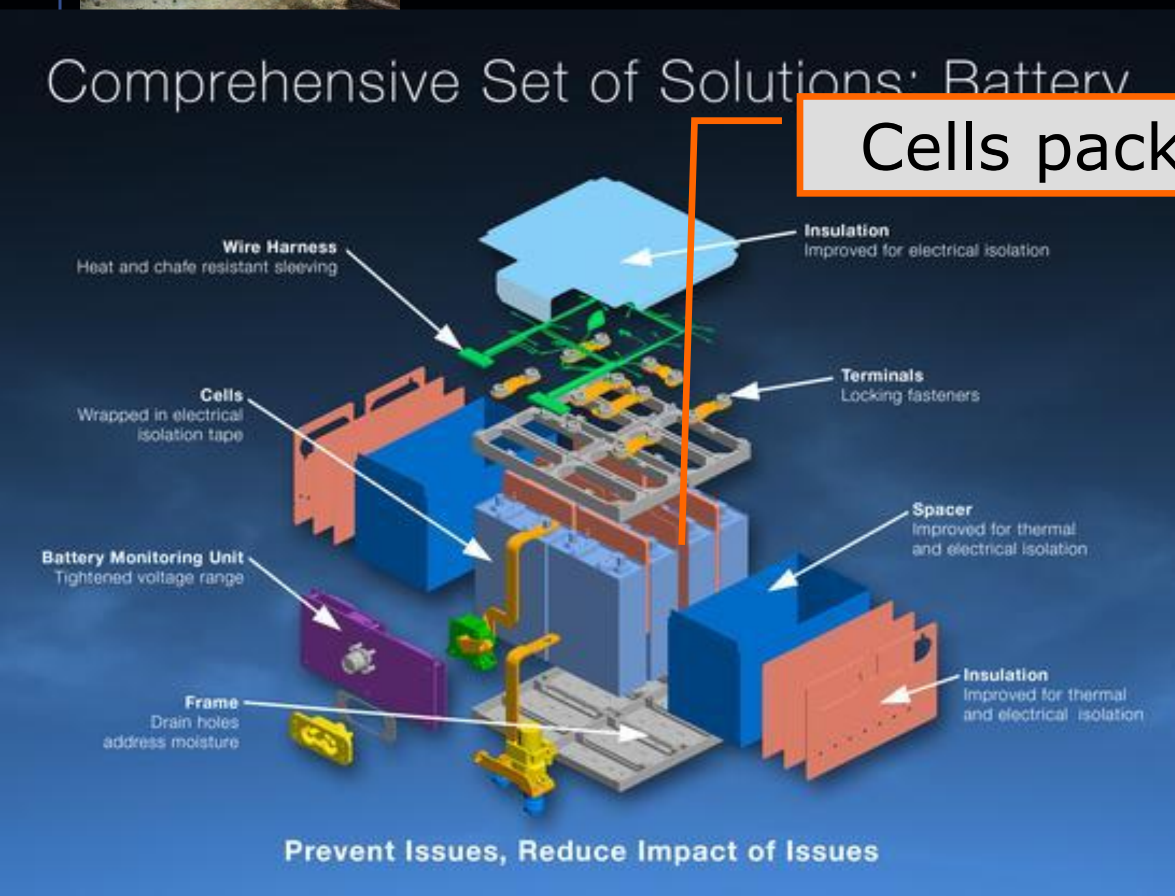
Instructive Example
787 Dreamliner Battery

Rapid Corrosion

Instructive Example



Large-format “safe” aviation cells

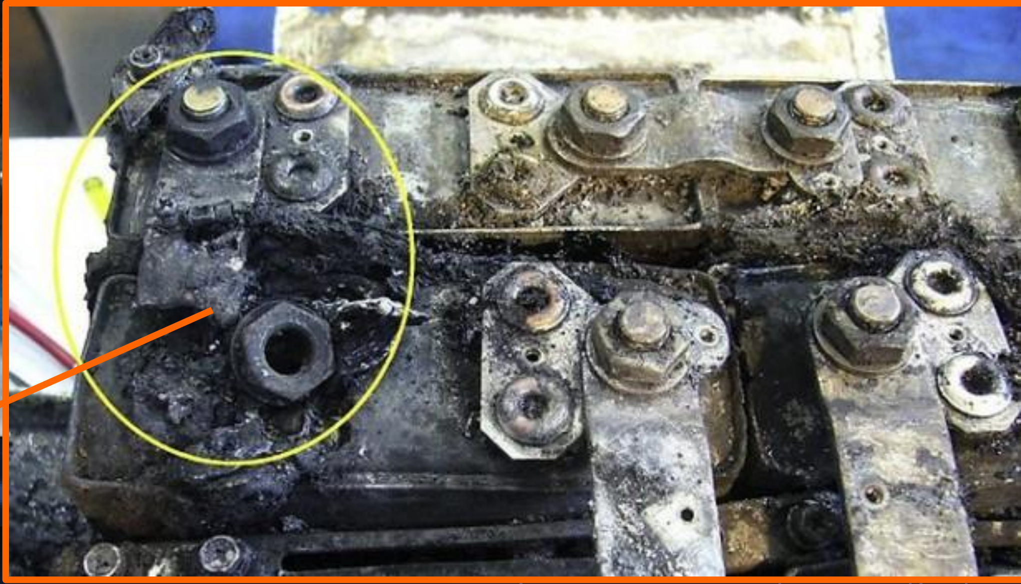


Cells packed closely together

Instructive Example

Closely-packed, large-format “safe” aviation cells

Fire propagated through the entire pack



Looks like the plug-in Prius failure

Instructive Example

examination of the flight recorder data from the JAL B-787 airplane indicate that the APU battery did not exceed its designed voltage of 32 volts.

-NTSB Press Release

What about individual cell voltages??

Some cells may have been overcharged

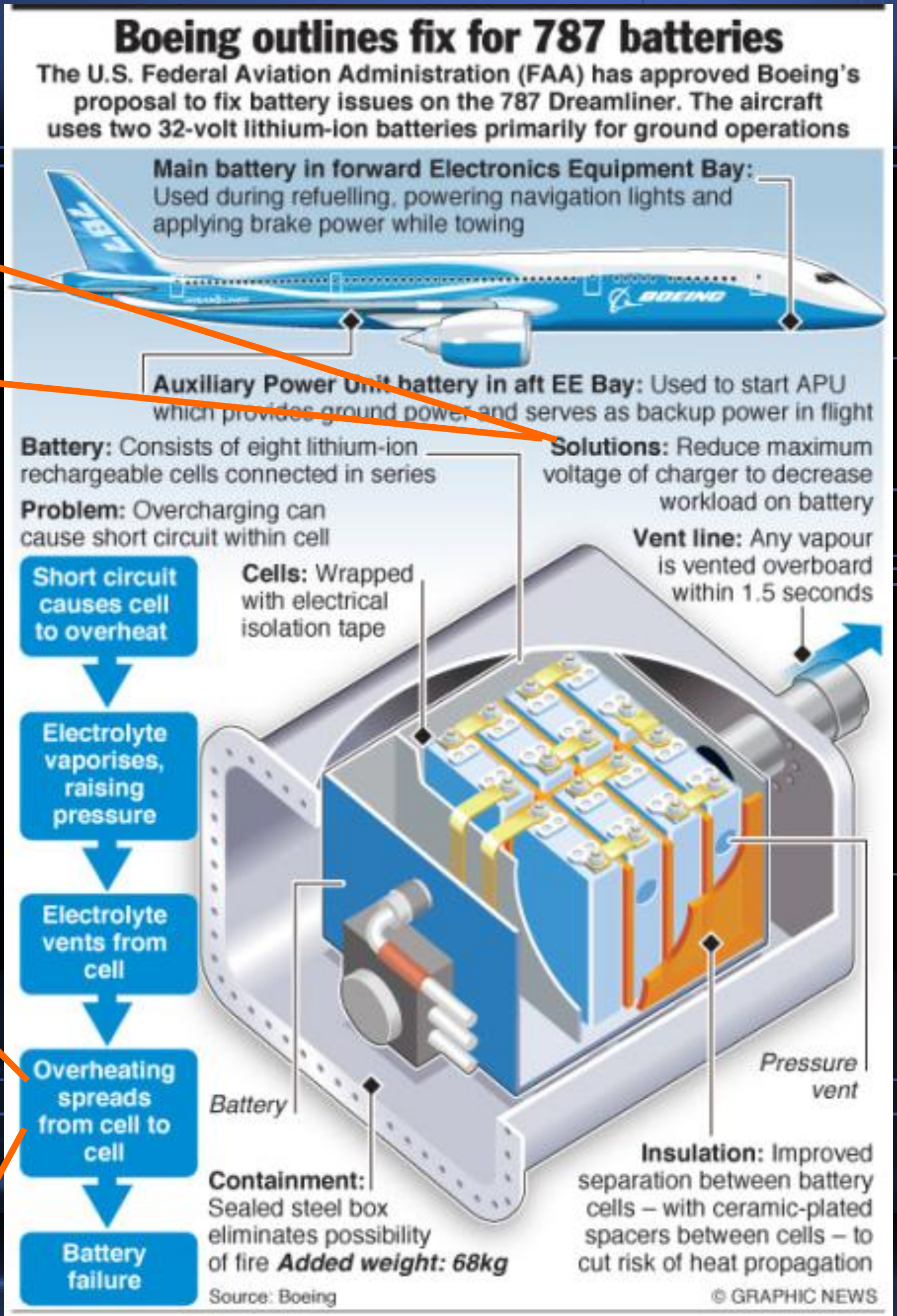
Boeing's Battery Fix

No!

Monitor and control every cell's voltage!

No!

Engineer to eliminate propagation!

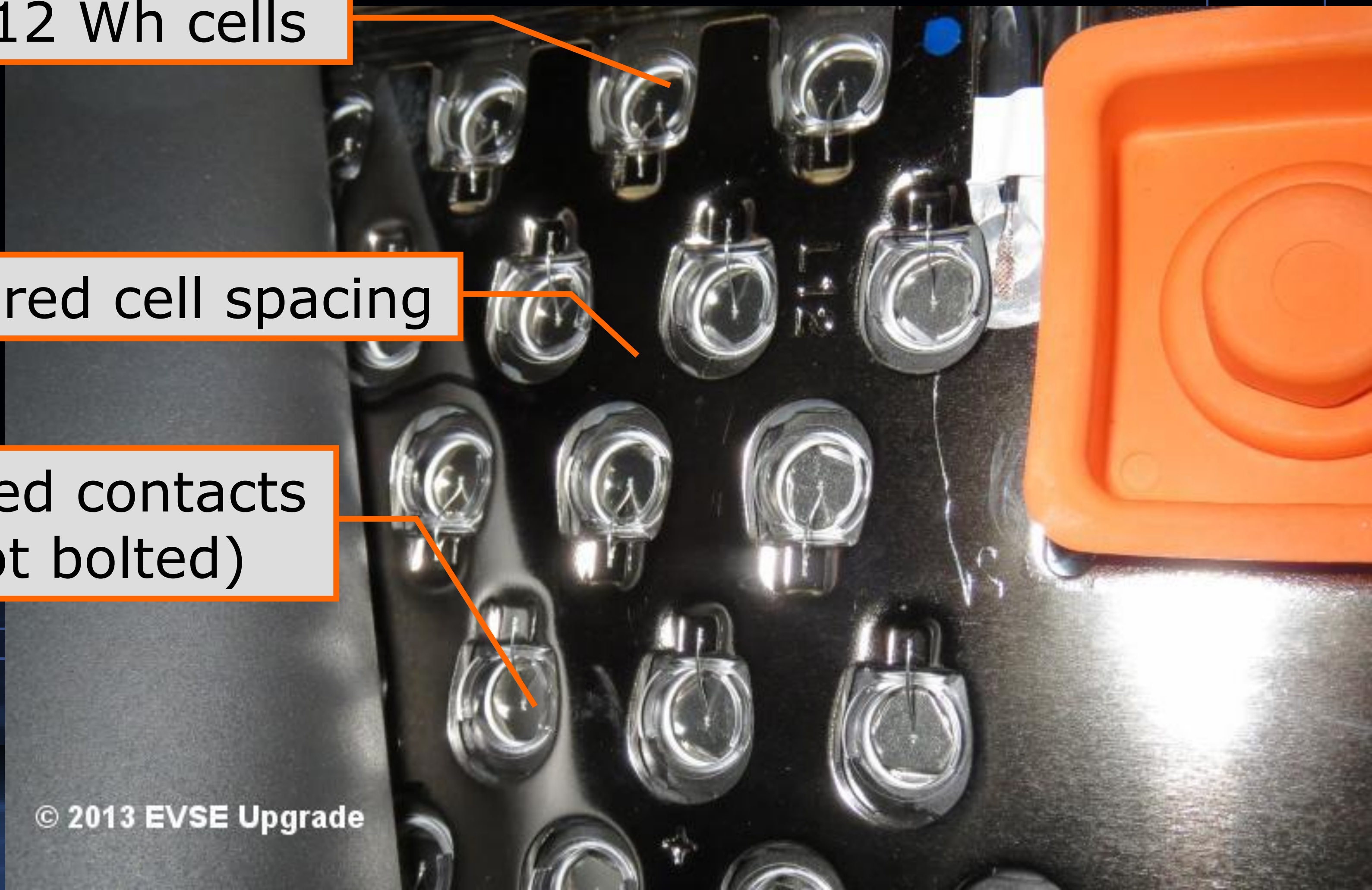


Tesla Model S Battery

Small 12 Wh cells

Engineered cell spacing

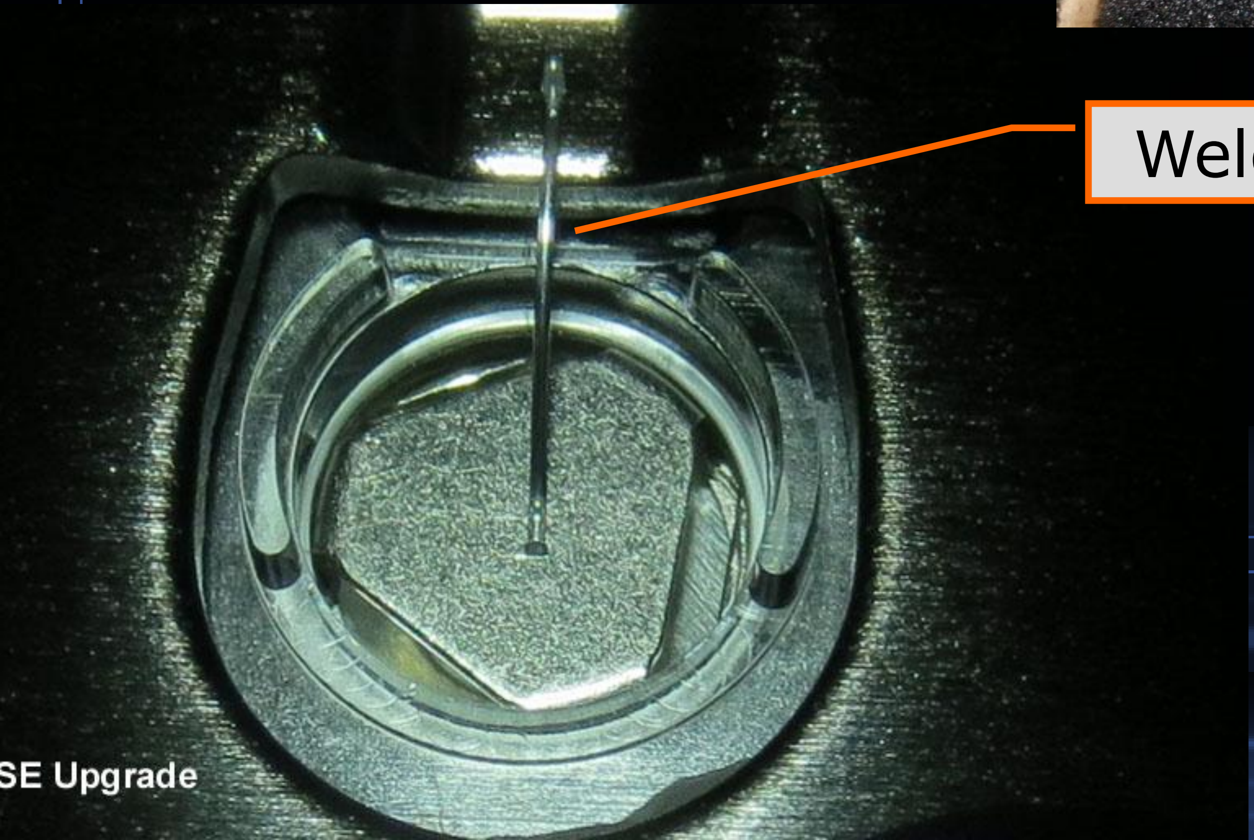
Welded contacts
(not bolted)



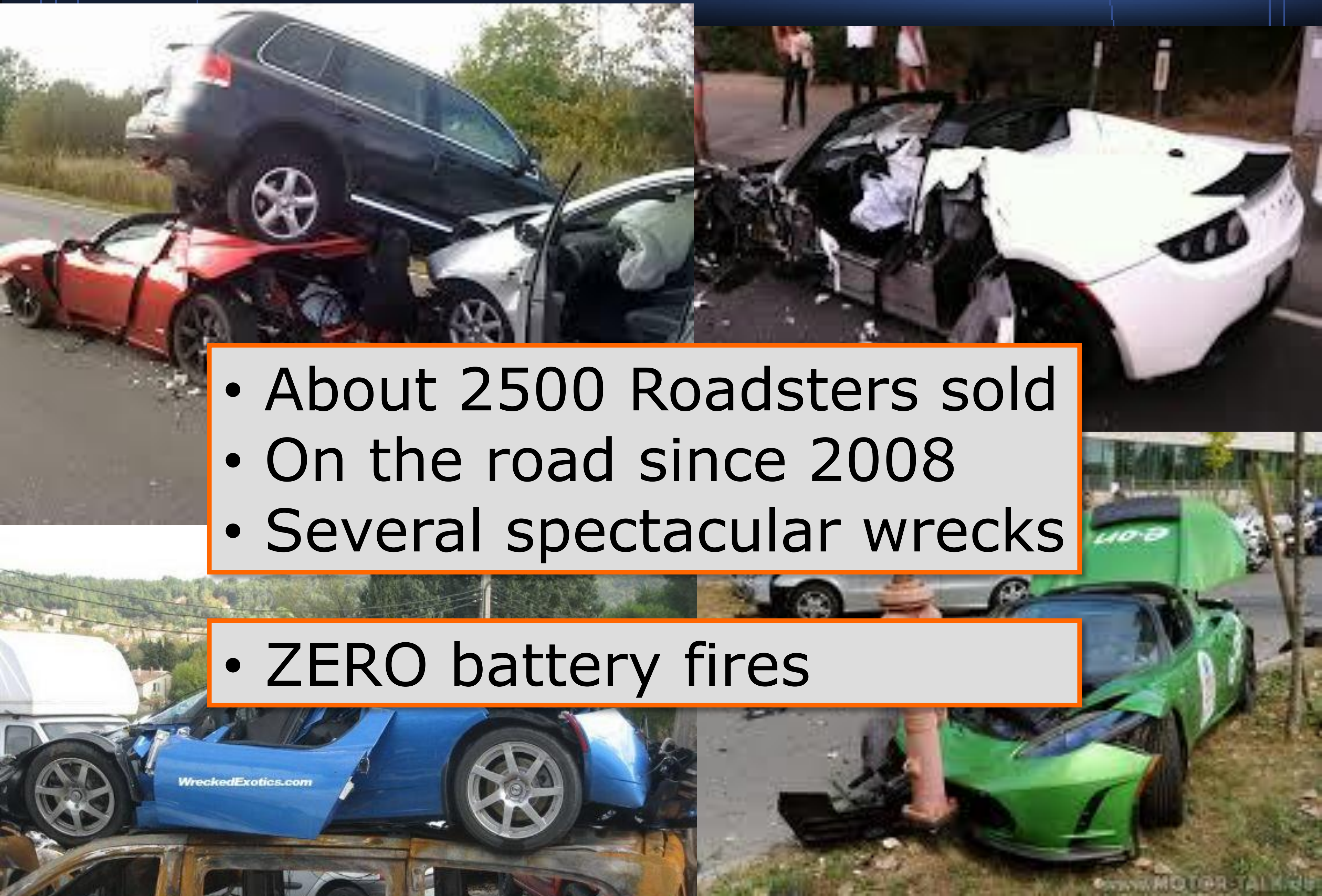
Tesla Model S Battery

Tesla's 18650 cells

Weld contact closeup



Tesla's Battery Safety Record



- About 2500 Roadsters sold
- On the road since 2008
- Several spectacular wrecks

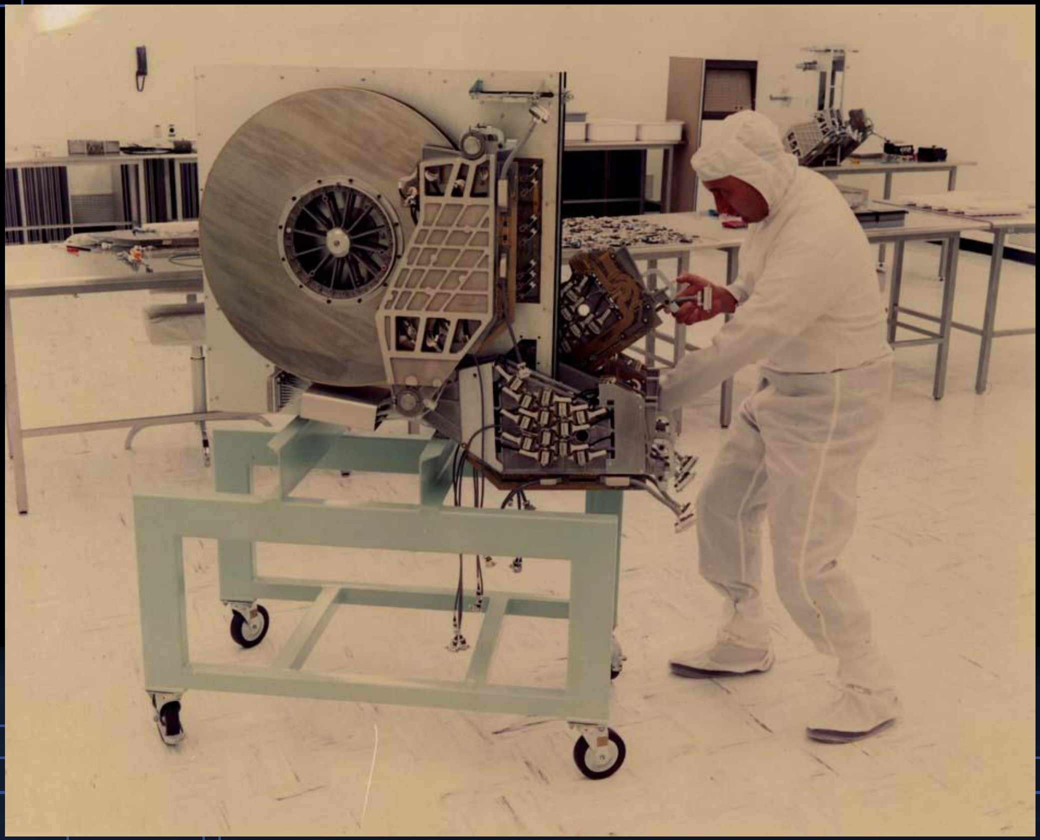
- ZERO battery fires

Technology Heads-Up

Technology Heads-Up 1

Mechanical complexity gets replaced with software

Software



Technology Heads-Up 1

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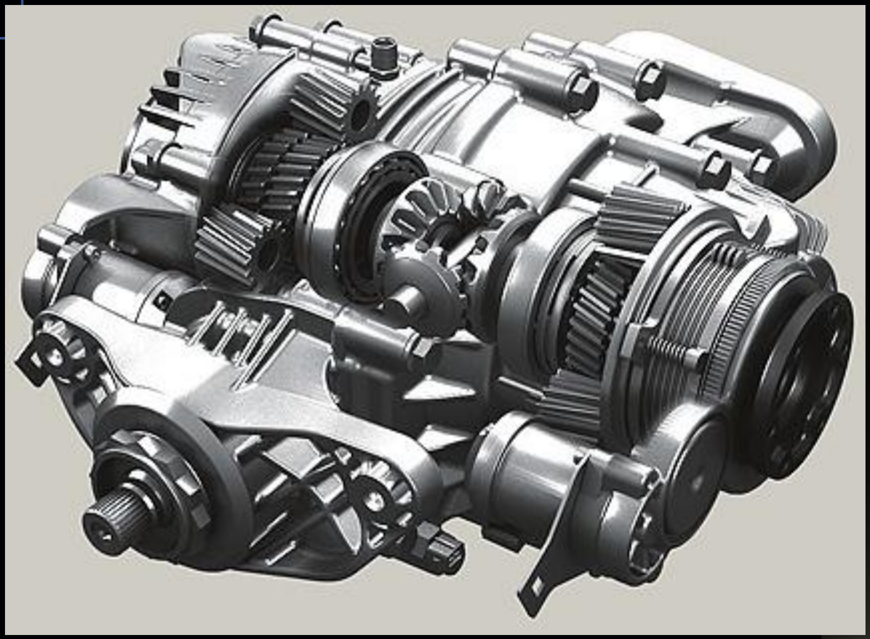
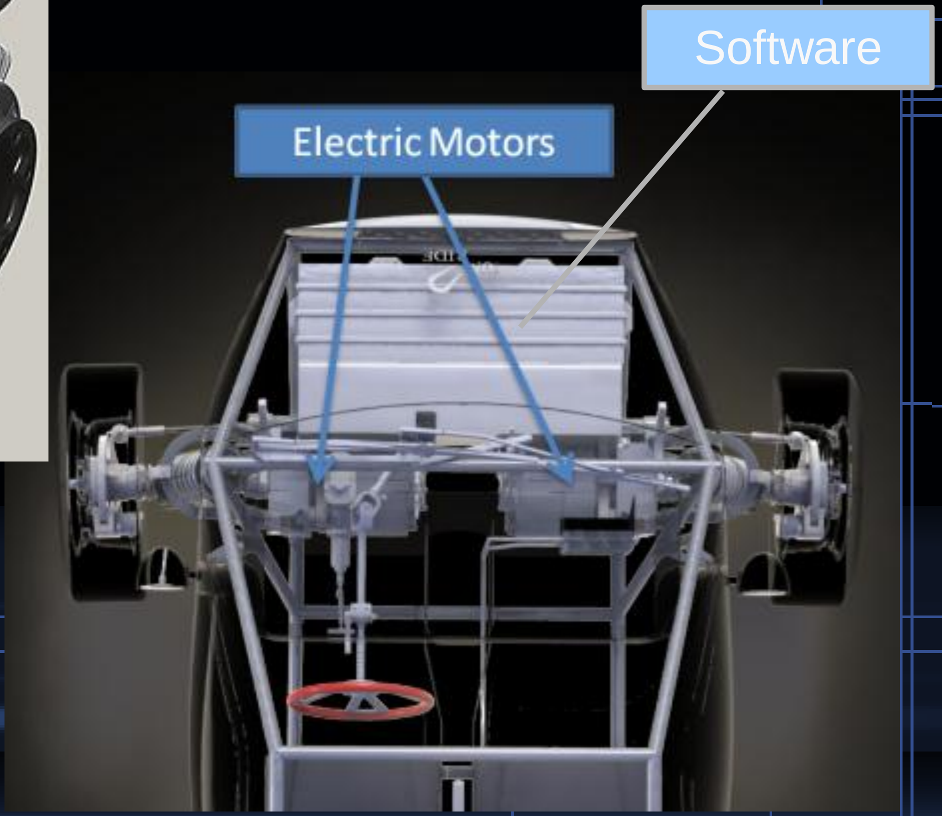


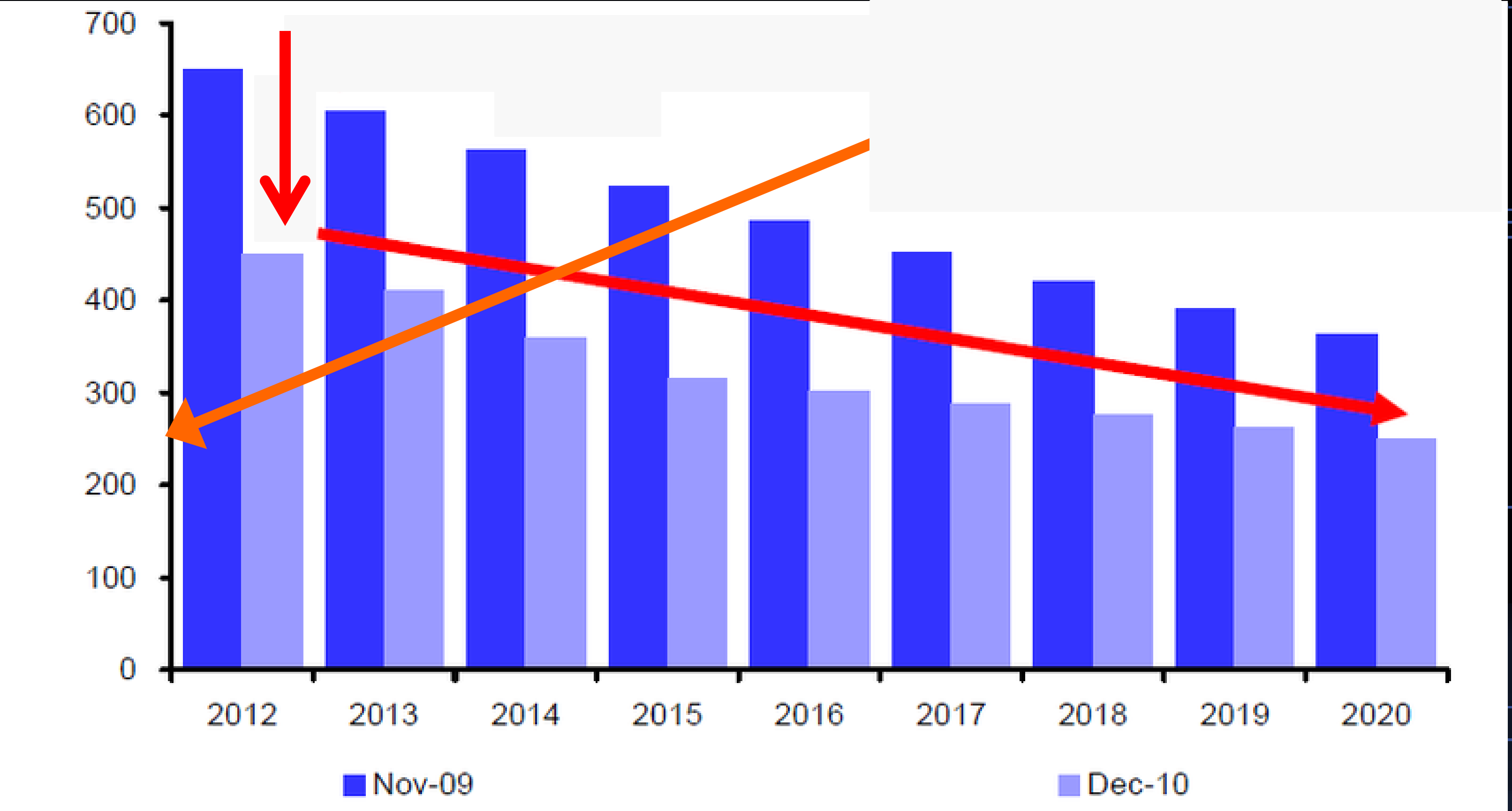


Technology Heads-Up 2

Battery prices are dropping quickly

Technology Heads-Up 2

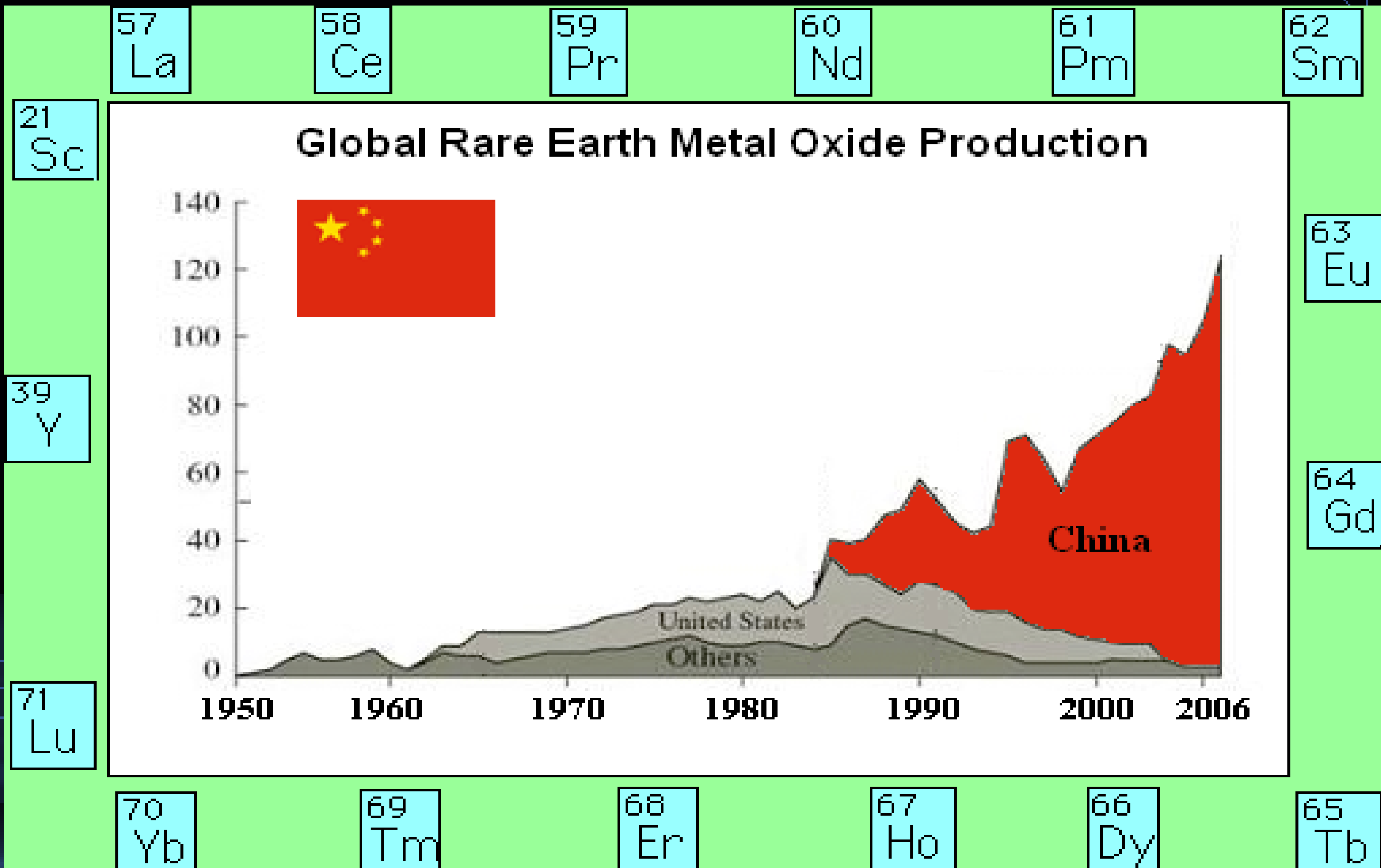
Deutsche Bank revises li-ion battery cost forecasts downward to $250/kWh by 2020



Source: DB Auto team, industry discussions and private interviews, Deutsche Bank

Technology Heads-Up 3

Resource Availability will Impact Scalability



Technology Heads-Up 3

Resource Availability will Impact Scalability

As hybrid cars gobble rare metals, shortage looms

-Reuters, August 31, 2009

Toyota Tries to Break Reliance on China

Company Seeks to Develop Electric Motor Without Costly, Tightly Controlled Rare Earth Metals

-Wall Street Journal, January 14, 2011

Conclusion

- Electric Vehicles are the best choice for cars
- Not many EVs so far, but the change is inevitable
- EVs pose unique engineering challenges

Thank you