Electric Future

Martin Eberhard
Topics

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

U.S. Oil Demand

Transportation: 68%
Industrial: 23%
Commercial: 2%
Residential: 4%
Electric Generation: 3%

The Problem

Oil for Transportation

- Passenger Cars/ Light Trucks: 51%
- Road Freight: 30%
- Air: 13%
- Rail: 2%
- Maritime: 2%
- Pipeline: 2%
- Oil for Transportation
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: 81.7%
- Gasoline Energy Content: 36066 Wh/gal
- Vehicle Mileage: 26 MPG
- Well-to-Wheel Energy Consumption: 1697 Wh/mi

**Best Case Gasoline Car: 41 MPG**
- Production Efficiency: 81.7%
- Gasoline Energy Content: 36066 Wh/gal
- Vehicle Mileage: 41 MPG
- Well-to-Wheel Energy Consumption: 1077 Wh/mi

Well-to-Wheel Energy Analysis

High Performance Electric Car: 150 Wh/km

Legacy Coal Electric Production

<table>
<thead>
<tr>
<th>Coal Plant Net Energy Ratio</th>
<th>US Electric Grid Efficiency</th>
<th>Charging Efficiency</th>
<th>Vehicle Mileage</th>
<th>Well-to-Wheel Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>29%</td>
<td>92%</td>
<td>90%</td>
<td>250 Wh/mi</td>
<td>1041 Wh/mi</td>
</tr>
</tbody>
</table>

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: 85%
- Electric Generation Efficiency: 45%
- US Electric Grid Efficiency: 92%
- Charging Efficiency: 90%
- Vehicle Mileage: 250 Wh.mi
- Well-to-Wheel Energy Consumption: 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'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.”

Well-to-Wheel Energy Analysis

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Energy Consumption Wh/mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Available Gasoline</td>
<td>1077</td>
</tr>
<tr>
<td>Legacy Coal</td>
<td>1041</td>
</tr>
<tr>
<td>Best Realistic Case Coal</td>
<td>769</td>
</tr>
<tr>
<td>Best Case Natural Gas</td>
<td>530</td>
</tr>
<tr>
<td>Pretty Good Gasoline</td>
<td>1697</td>
</tr>
</tbody>
</table>

Note: you don’t need these fossil fuels for EVs
Are EVs more efficient than other “green” cars?
What about Hydrogen Fuel Cells?

Hydrogen (H₂) is converted into electricity within the fuel cell, which then powers the electric drive motor. The process also produces water as a byproduct.
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

Electric Energy Storage

Storage efficiency = \frac{Electricity \text{ in}}{Electricity \text{ 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.

**H₂ Production**
- Electrolysis: 70% efficient
- Compression: 70% efficient

**H₂ Fuel Cell Car**
- Electric Energy Storage: Storage efficiency = 20% (highly optimistic)
- H₂ Fuel Cell: 40% efficient

**Battery Electric Car**
- Electric Energy Storage: Storage efficiency = 85%
- Charger: 92% efficient
- Li Ion Battery: 93% efficient

**1 MWh Electricity**

- 1100 mi. for H₂ Fuel Cell Car
- 3600 miles for Battery Electric Car
Q: How far will one unit of biomass power a car?

Biomass efficiency = \( \frac{\text{miles driven}}{\text{Ton of biomass}} \)
Silly Q: How far will one unit of biomass power a car?

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

1. Iogen enzymatic process, gallons of gasoline equivalent
2. Southern Company Services
Better Q: How far will an acre of land power a car per year?

Energy Conversion
land efficiency = ______ miles driven
acre of land per year

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

1 acre of farmland

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

Corn Farming
125 bu/acre per year

Ethanol Production
1.94 GGE/bu

IC Engine
45 miles per gallon

Ethanol Production

Energy input
1.91 GGE/BU

Co-product credit
0.35 GGE/BU

11K miles

2,100 miles

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. \(1.658 \times 10^{12}\) miles in 2002 (DOT Bureau of Transportation Statistics)
2. cia.gov
Better Q: How far will an acre of land power a car per year?

- Ethanol Production
  - Energy Conversion (highly optimistic) efficiency = 11,000 miles per acre per year
  - Corn Farming: 125 bu/acre per year
  - Ethanol Production: 1.94 GGE/BU
  - IC Engine: 45 miles per gallon

- Ethanol ICE Car
  - Energy input: 1.91 GGE/BU
  - Co-product credit: 0.35 GGE/BU

1 acre of farmland

11K miles
2,100 miles

2. 2.7 gal ethanol/bu / 1.39 gal ethanol/gge
**How about Cellulosic Ethanol?**

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

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

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

1. 1.658 x 10¹² miles in 2002 (DOT Bureau of Transportation Statistics)
2. cia.gov
Q: What area is required to offset 50% of Passenger car miles driven in the USA?¹

¹ 1.658 x 10¹² miles in 2002 (DOT Bureau of Transportation Statistics)
² cia.gov
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?

Energy Conversion

\[ \text{efficiency} = \frac{\text{miles driven}}{\text{Gallon of biodiesel}} \]

\[ X \text{ miles} \]
Q: How many miles will one gallon of diesel power a car?

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

1 gallon (bio)diesel → Diesel Car → Diesel Engine 1: 38 miles per gallon

1 gallon (bio)diesel → Electricity Production → 18.21 kWh per gal 2: Diesel generator 18.21 kWh per gal → 65 miles

1 gallon (bio)diesel → Electric Car → Electric car 3.6 miles per kWh → 38 miles

1. 2006 VW Diesel Beetle (EPA)
2. e.g. Anguilla Electric Company, 2001 average
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
Plug-in Hybrid conversion with A123 (LiFePo) cells

Instructive Example

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
Instructive Example

Full vehicle fire caused by “safe” LiFePo battery pack
For any type of cell, for any battery system

- All 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 prevent propagation
- 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
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)

© 2013 EVSE Upgrade
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
Technology Heads-Up 1

Mechanical complexity gets replaced with software
Battery prices are dropping quickly
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

Global Rare Earth Metal Oxide Production

China
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