



Natural Gas Vehicle Conference & Expo
Atlanta GA, November 21, 2013

Driving Across the Valley of Death

Investing in Technology Innovation to
Overcome Market Entry Hurdles

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Program Director
Advanced Research Projects Agency-Energy
U.S. Department of Energy

Fact is, natural gas is a
poor transportation fuel

Gasoline



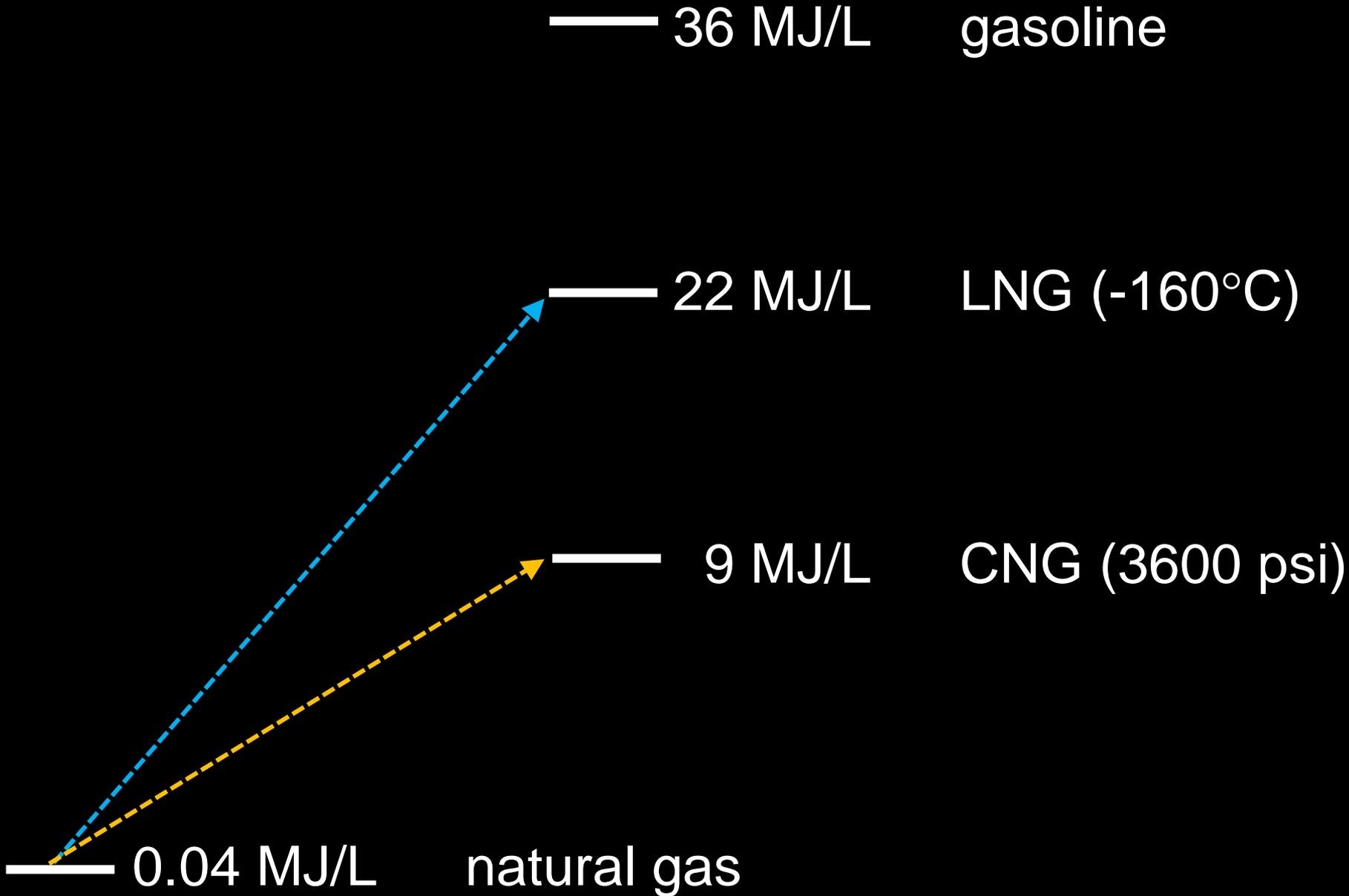
10 gallons per minute = 20 megawatts

— 36 MJ/L gasoline

— 22 MJ/L LNG (-160°C)

— 9 MJ/L CNG (3600 psi)

— 0.04 MJ/L natural gas



The Good

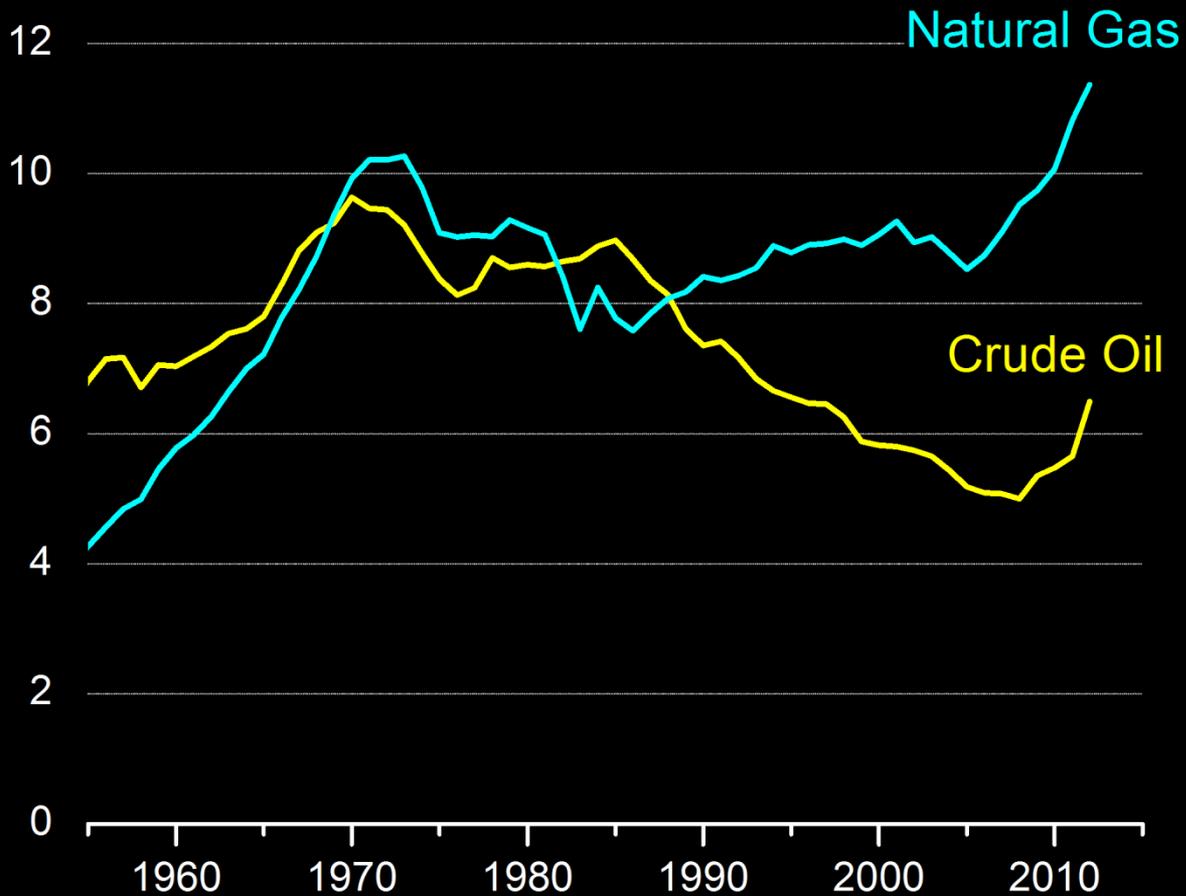


the natural gas boom

America's got gas!

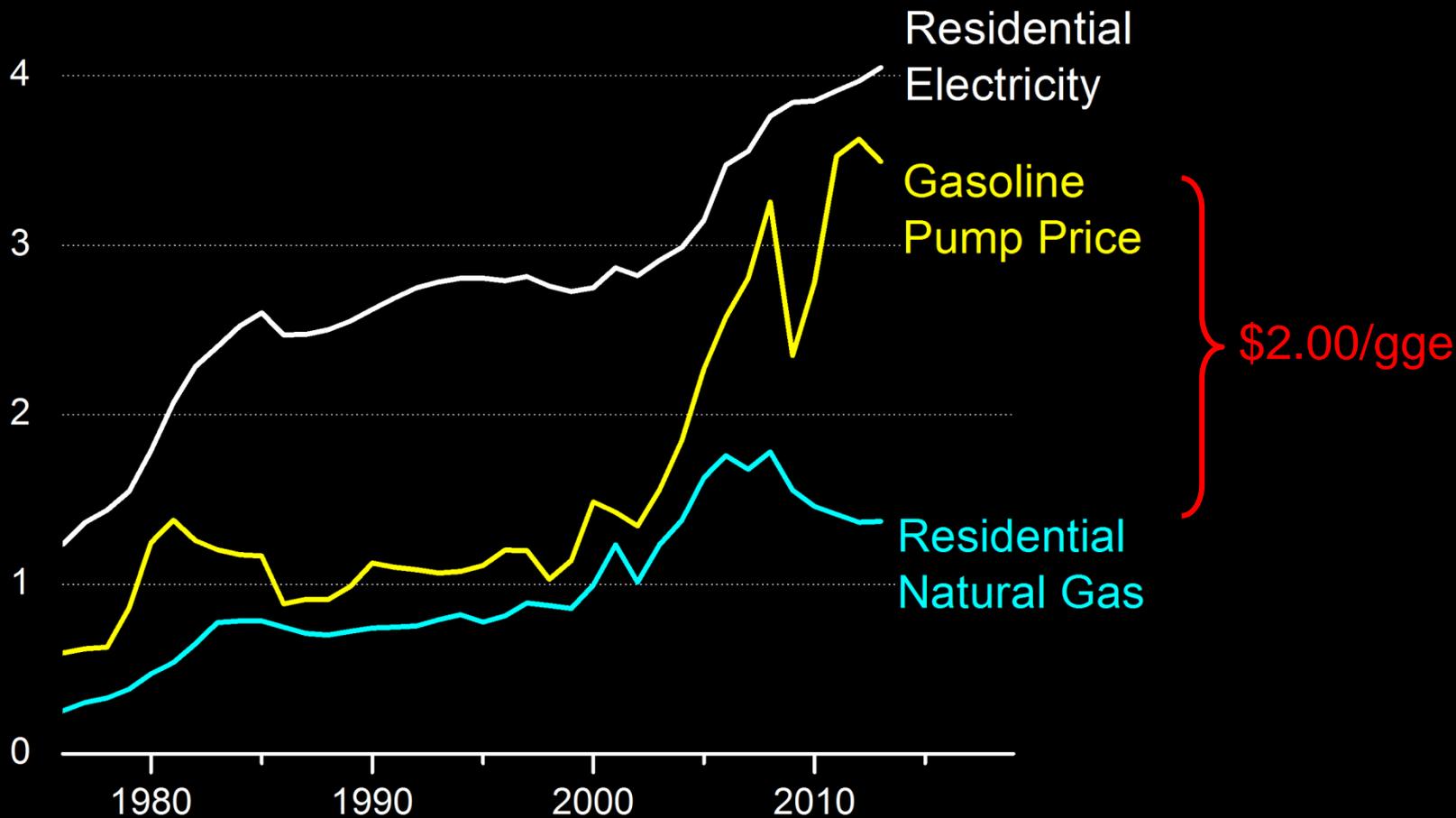
U.S. Production

(million barrels per day)



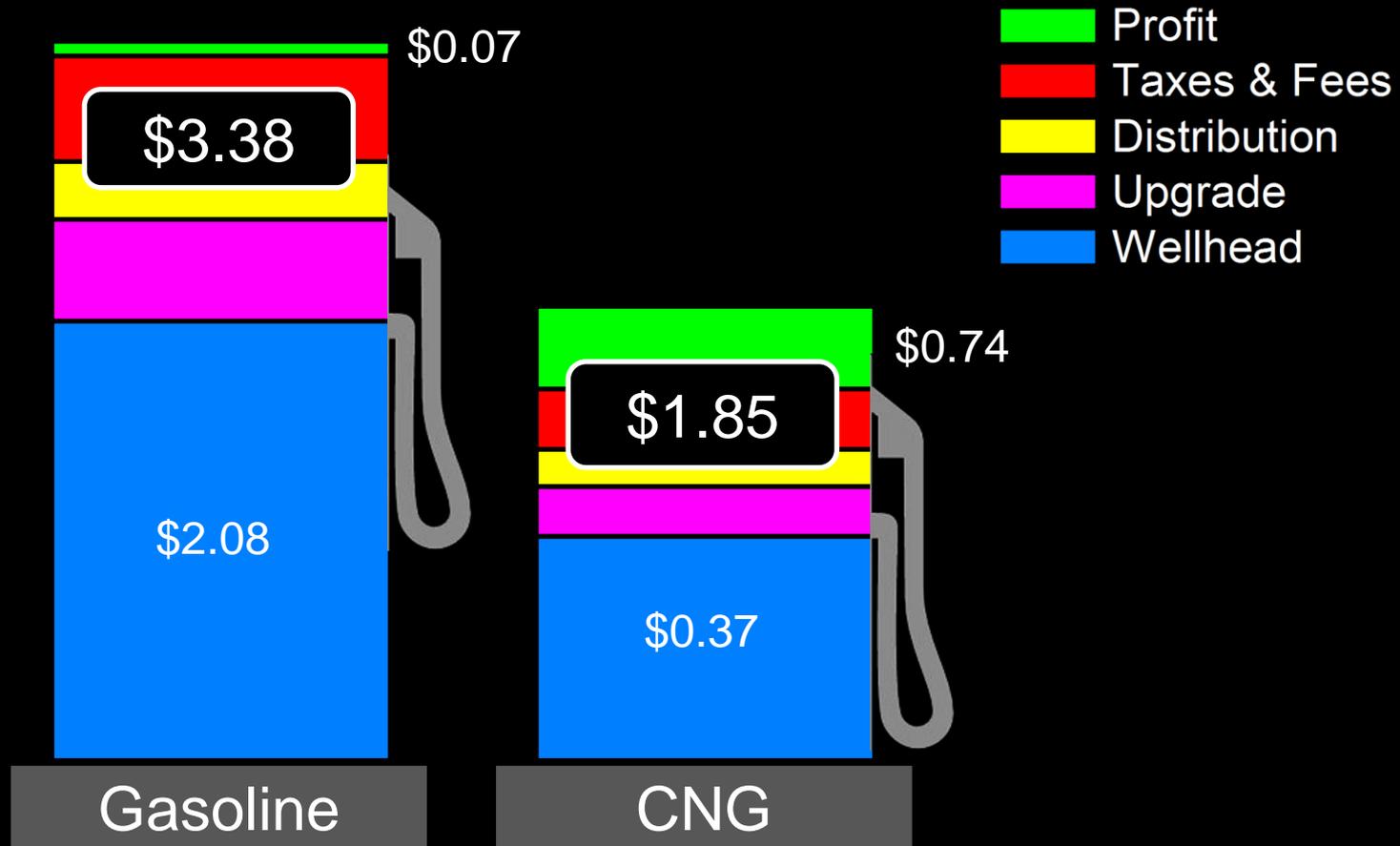
U.S. Fuel Prices

(nominal dollars per gallon)

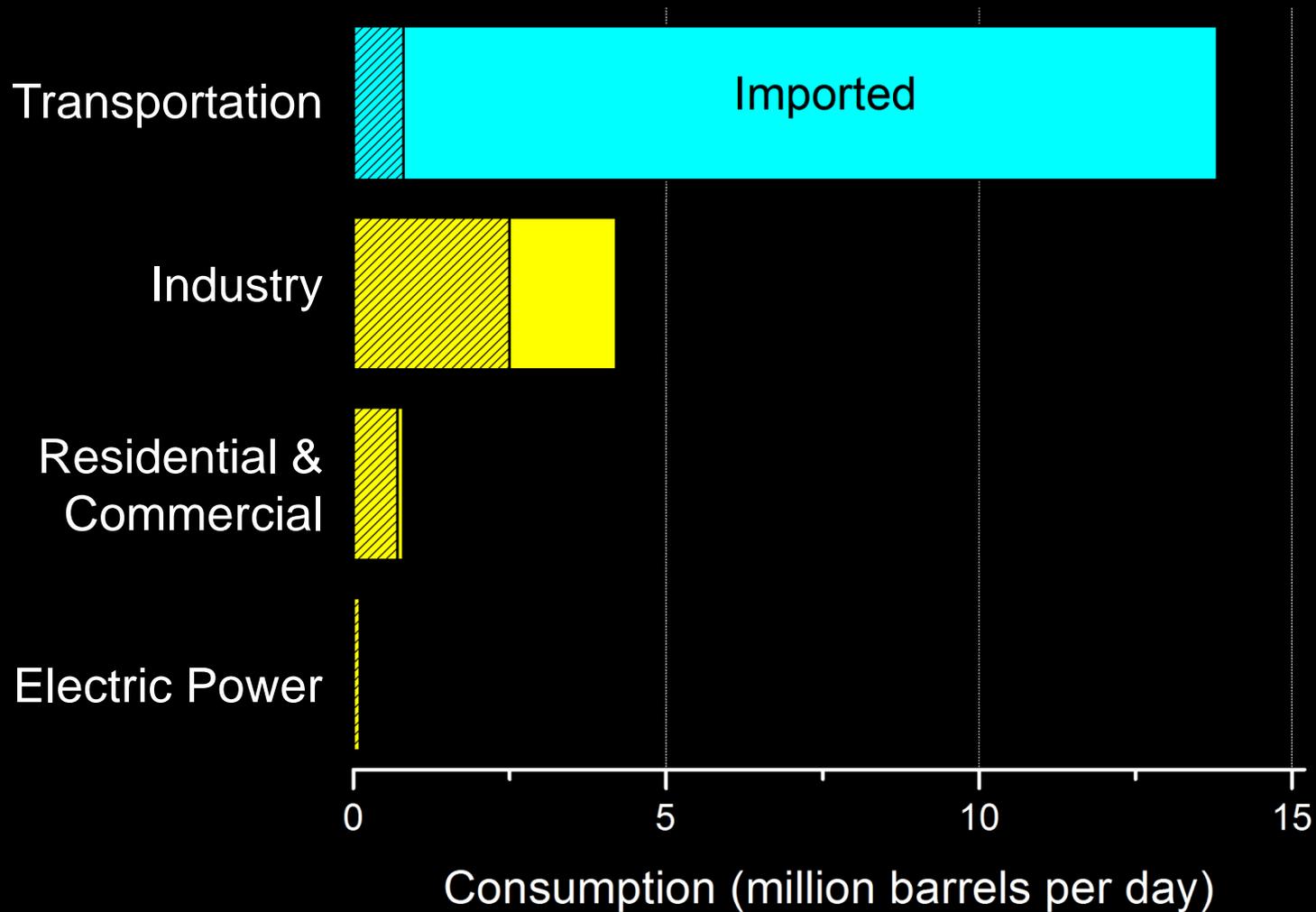


U.S. Fuel Pump Prices

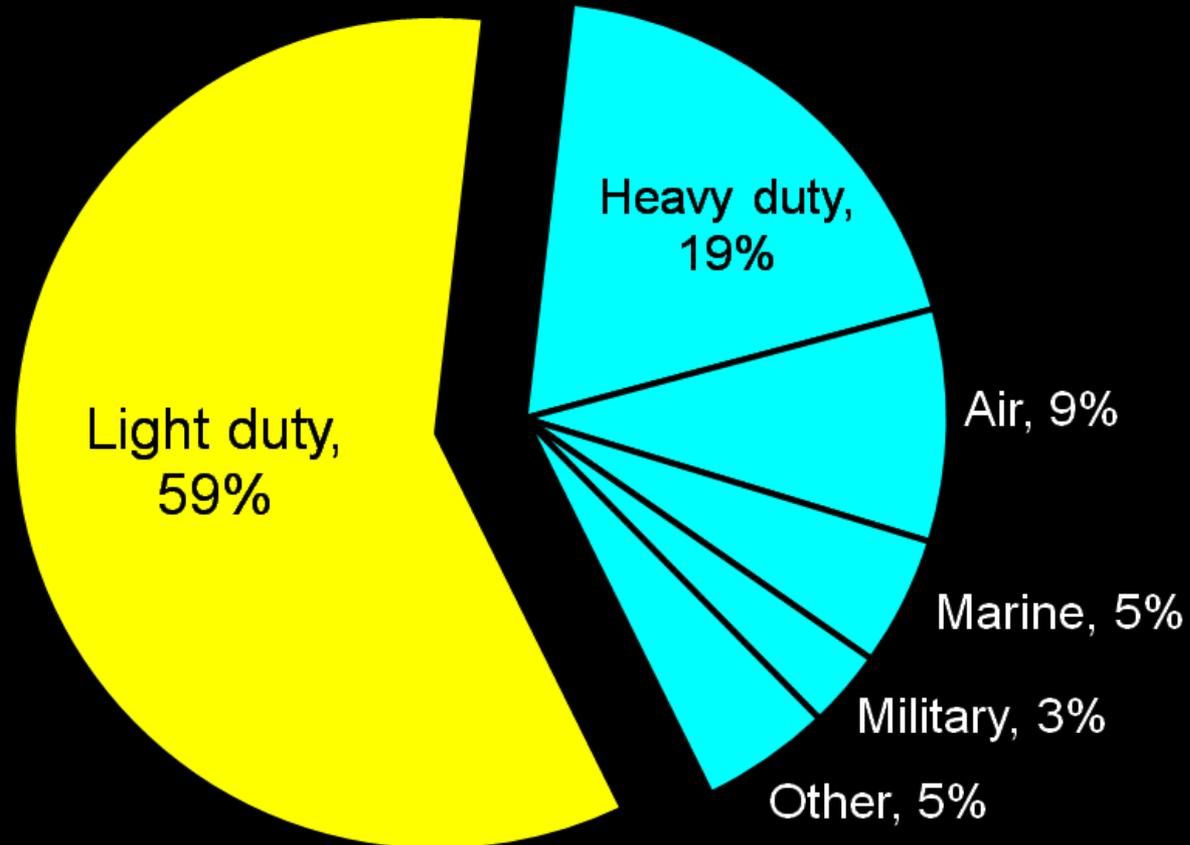
(per gallon equivalent)



2010 U.S. Oil Consumption

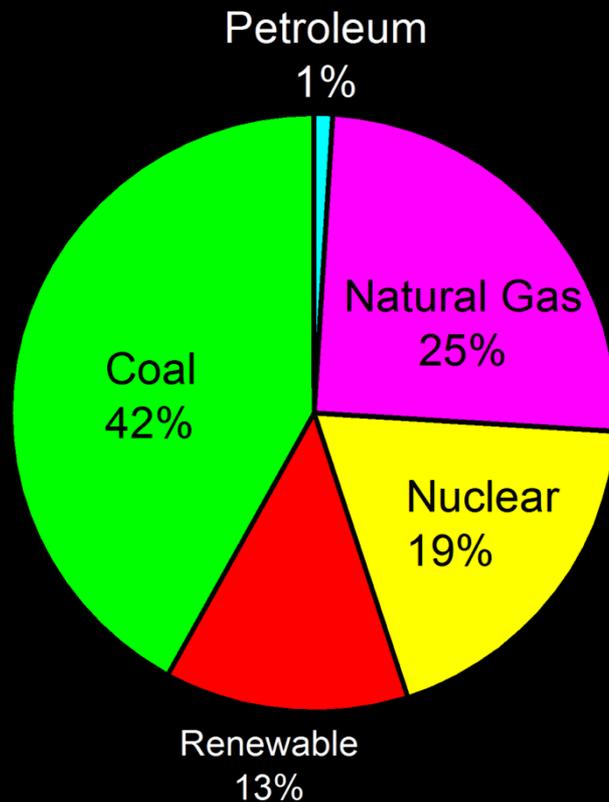


2010 U.S. Transportation Energy

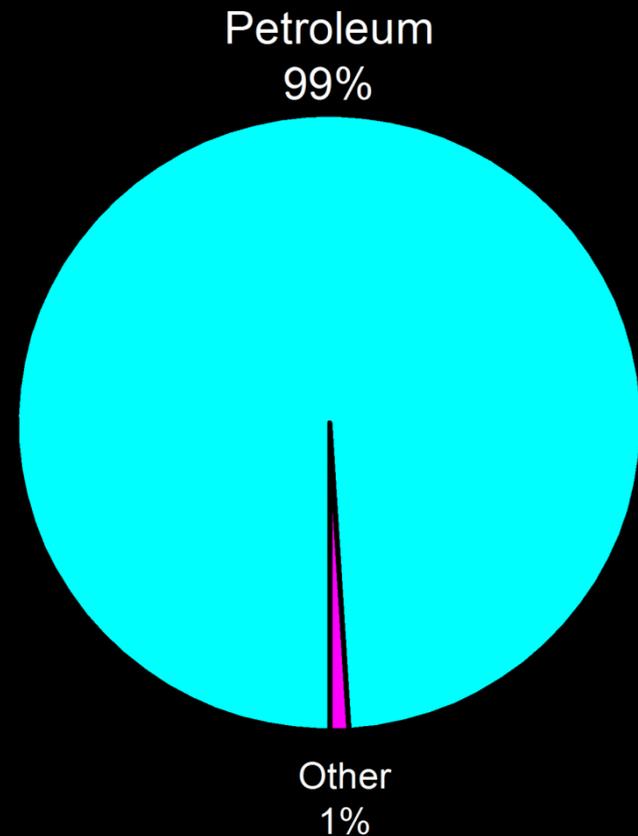


What's wrong with this picture?

U.S. Electric Power



U.S. Transportation



Investing 101

Diversification is the most important component of reaching long-range financial goals while minimizing risk

Energy Security

Low cost, abundant natural gas presents an unprecedented opportunity to diversify our transportation energy infrastructure

The Bad



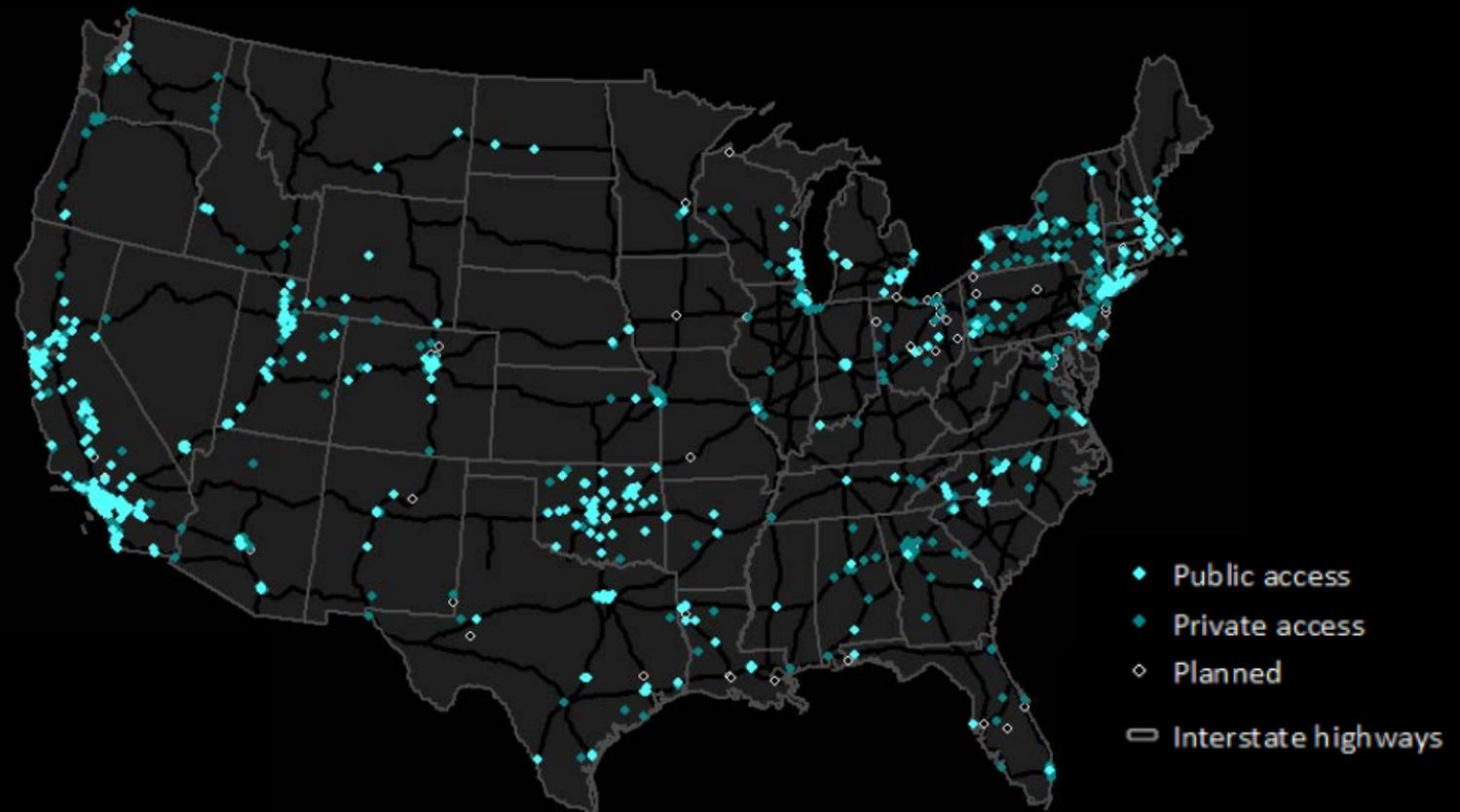
NGV challenges

Where is the gas station?



Challenge #1: Infrastructure

(632 CNG fueling stations)



Source: U.S. Energy Information Administration, based on U.S. Department of Energy (DOE), Alternative Fuels & Advanced Vehicles Data Center, as of March 27, 2012

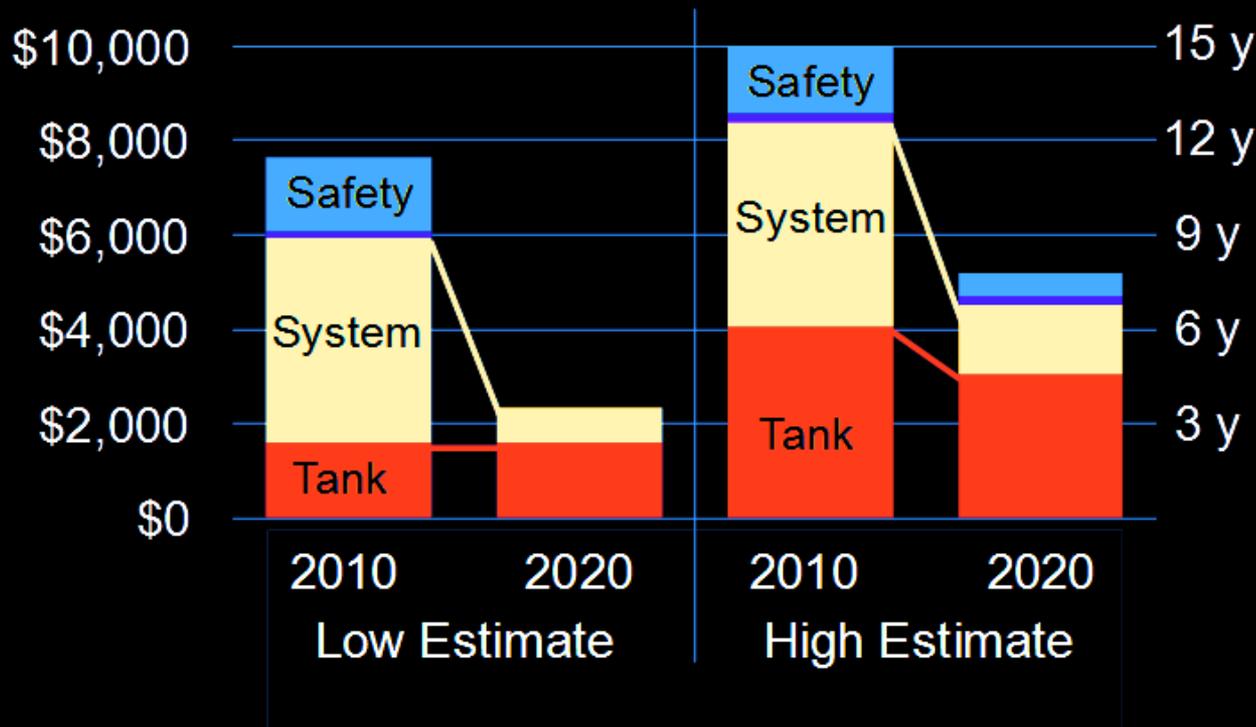
Can I put my luggage in the trunk?
Uh, sorry no



Challenge #2: Storage Cost

Added Cost

Payback



$$\text{Payback} = (\text{Cost} \times 35 \text{ mi/gge}) / (12,000 \text{ mi/yr} \times \$2.00/\text{gge})$$

The Ugly



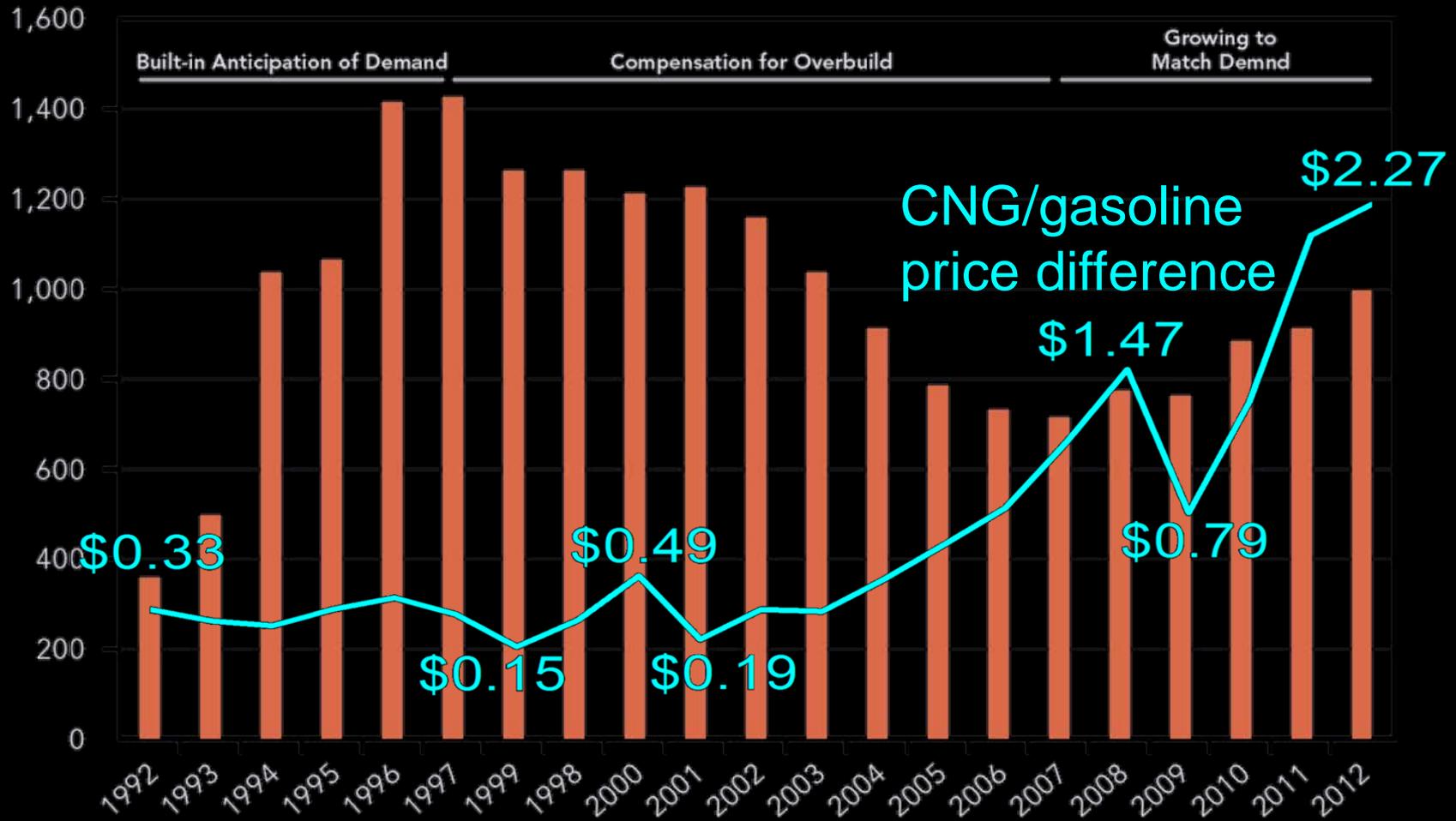
consumer adoption

Deja Vu



CNG Home Refueling
T. Boone Pickens' Backyard, 1992

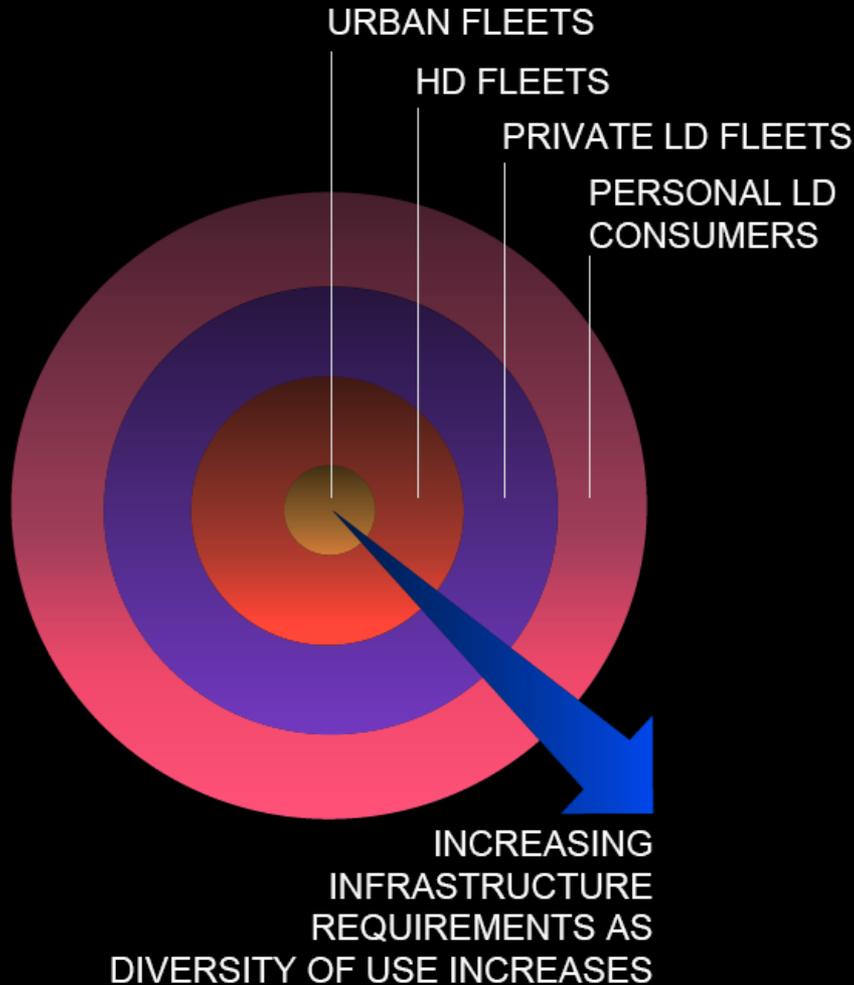
Number of CNG Stations (1992-2012)



How do we not repeat the past?

**We need to better understand
what drives consumer behavior**

NGV Adoption



Businesses

want payback on investment

Consumers

want same performance and convenience plus added benefit

Why would someone want to buy a NGV?

Economics

Convenience

Image

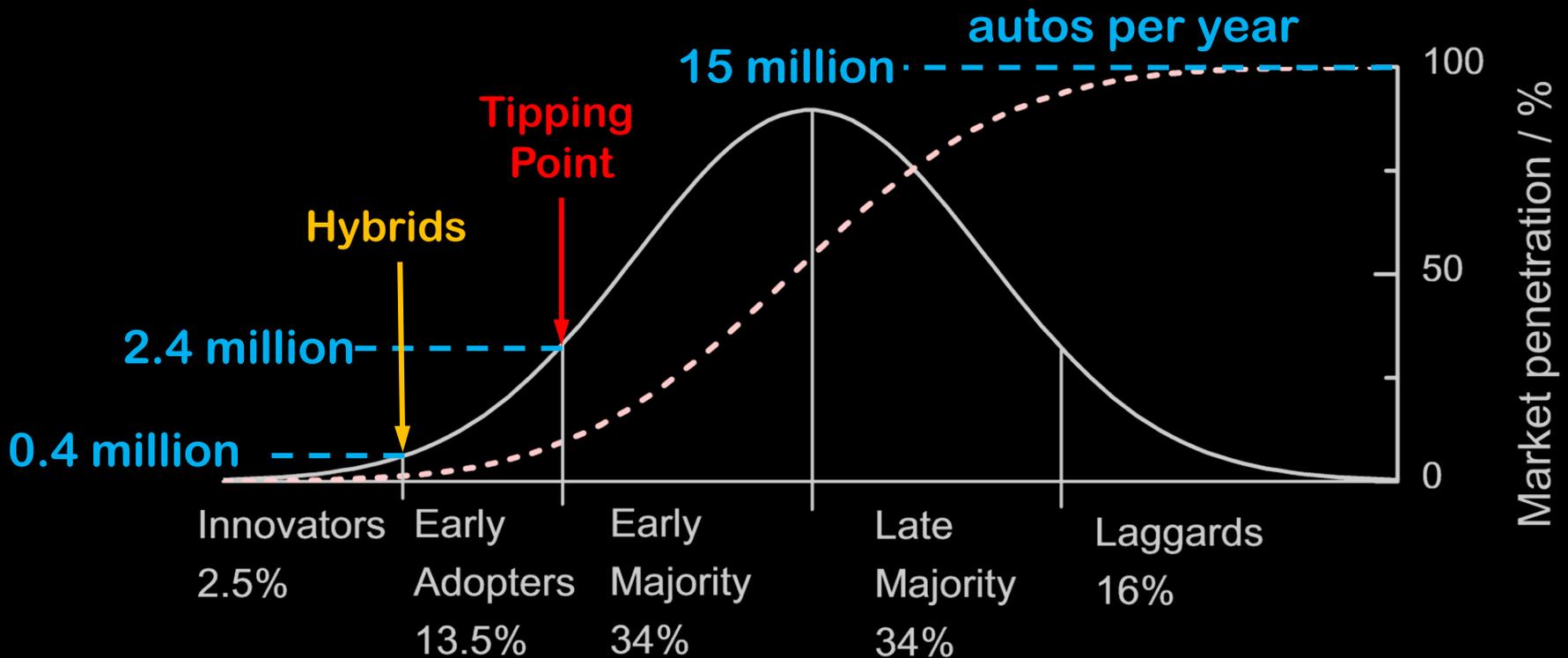
Economic Comparison

		Gasoline	Hybrid	NGV	EV
Annual mileage	mi/yr	12,000	12,000	12,000	12,000
Fuel efficiency	mpg	35	45	35	100
Annual fuel use	gge/yr	343	267	343	120
Fuel price	\$/gge	3.6	3.6	1.4	3.9
Annual fuel cost	\$/yr	1,234	960	480	468
Annual savings	\$/yr	—	274	754	766
Vehicle price	\$	19,000	23,000	31,000	37,000
Price difference	\$	—	4,000	12,000	18,000
Simple payback	yr	—	15	16	23

**None of these make economic sense...
why do people buy them?**

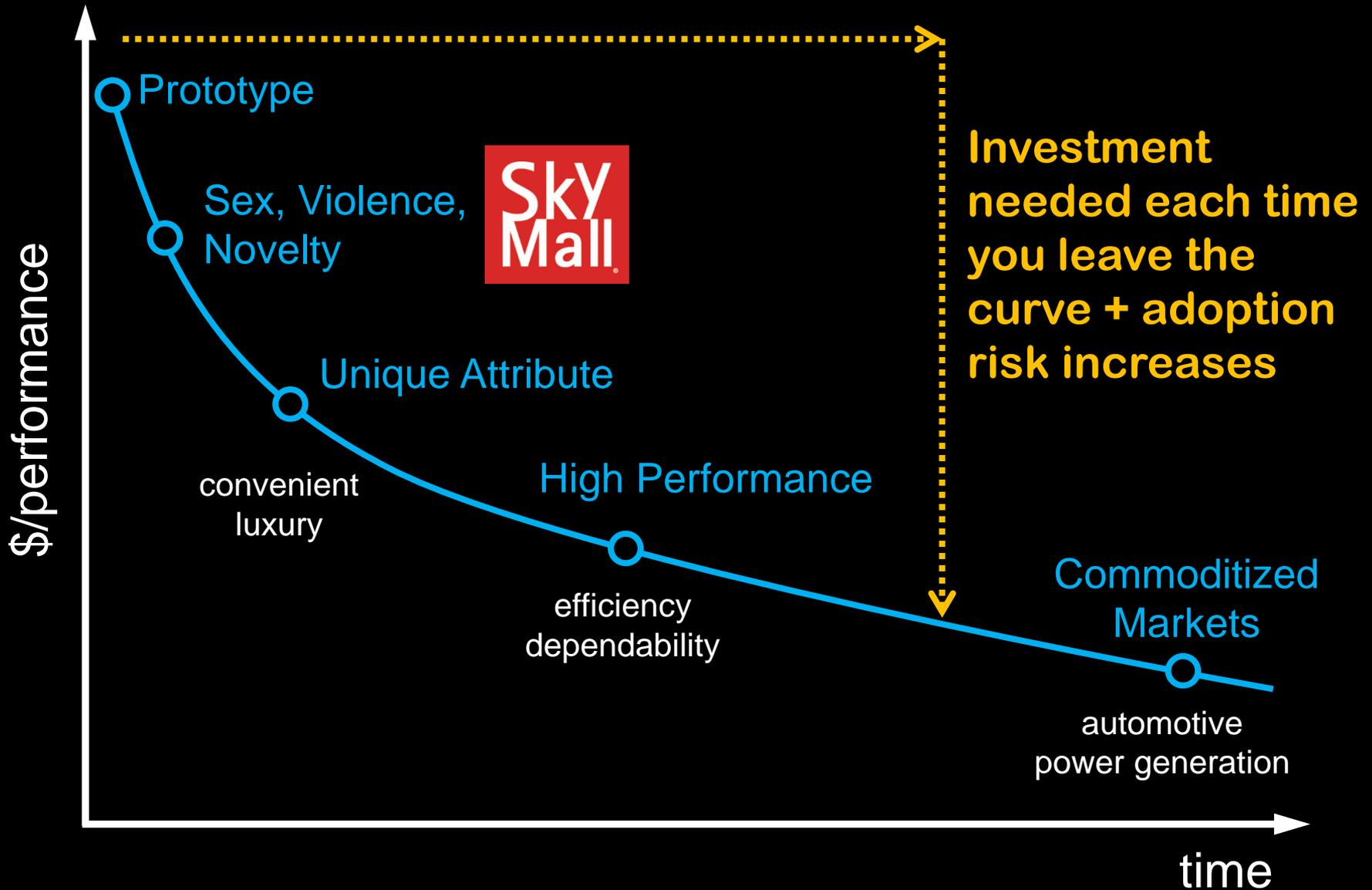
Diffusion of Innovation

U.S. Light Duty Auto Market



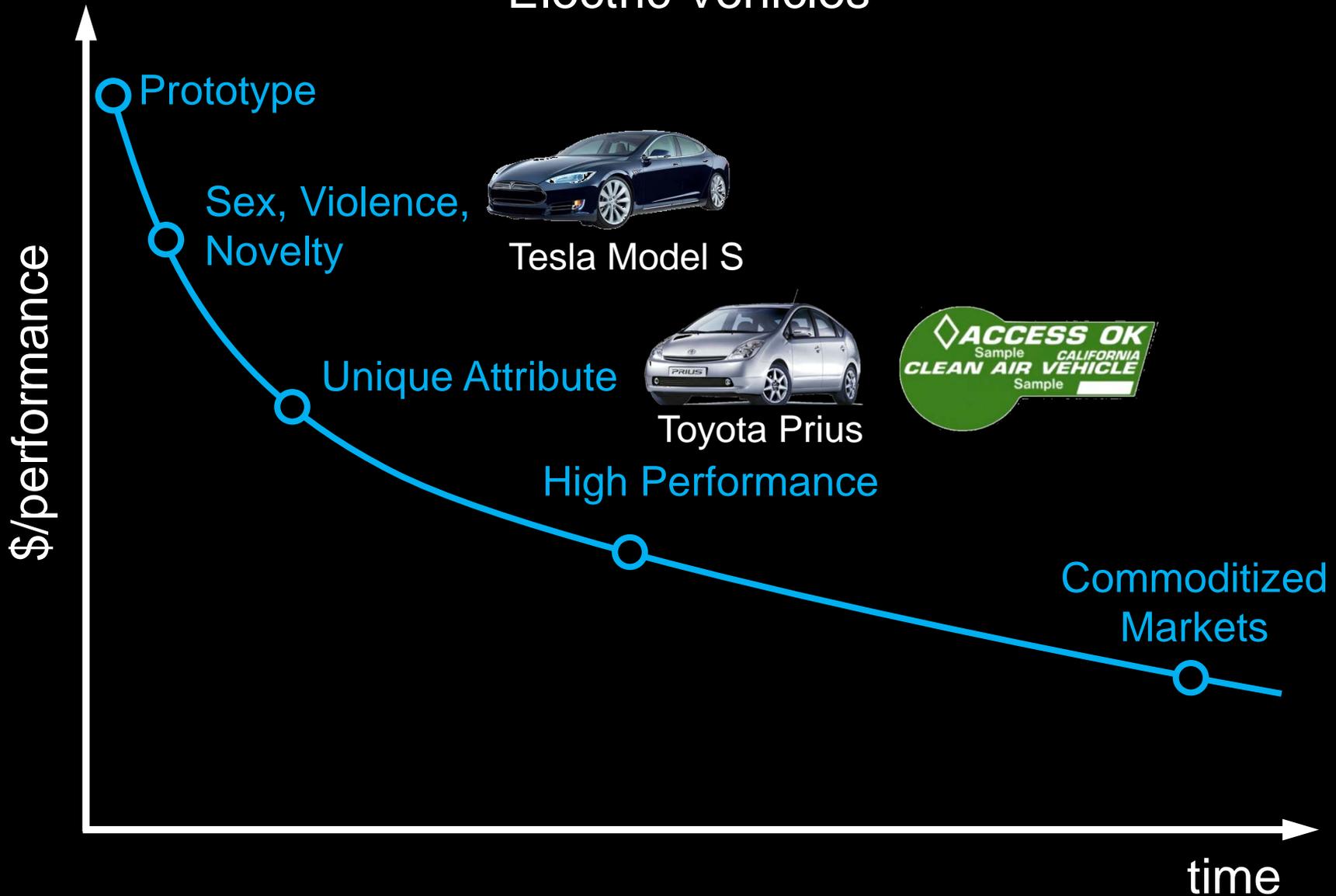
Hybrids hit 3.0% of total sales in 2012

Adoption of New Technology



Adoption of New Technology

Electric Vehicles



Is the future a gasoline-CNG duel fuel?

Maybe not, here is why

California High Occupancy Vehicles (HOV)

White Clean Air Vehicle Stickers

- all electric, H2 fuel cell, CNG vehicles
- unlimited number expires Jan 2019



Green Clean Air Vehicle Stickers

- plug-in hybrid vehicles
- first 40,000 applicants expires Jan 2019



Yellow Clean Air Vehicle Stickers

- hybrid vehicles
- program ended Jul 2011



Hybrid Sales and HOV Access Impact in California

- California accounts ~ 50% of EV sales each month
- GM Volt
 - Initially launched without meeting HOV lane requirements
 - 10% sold in California before changes for HOV in 2011
 - 28% sold in California after changes for HOV in 2012
 - 9 out of 10 Volt buyers primarily motivated by HOV access
- Toyota Prius
 - 80% Prius Plug-ins were sold in California in 2012
 - Prius hybrid retained significant resale value if had HOV sticker

NGV adoption will require
identifying a unique feature

Government Investment



technology innovation



Alex Crawley

Energy Research and
Development Administration

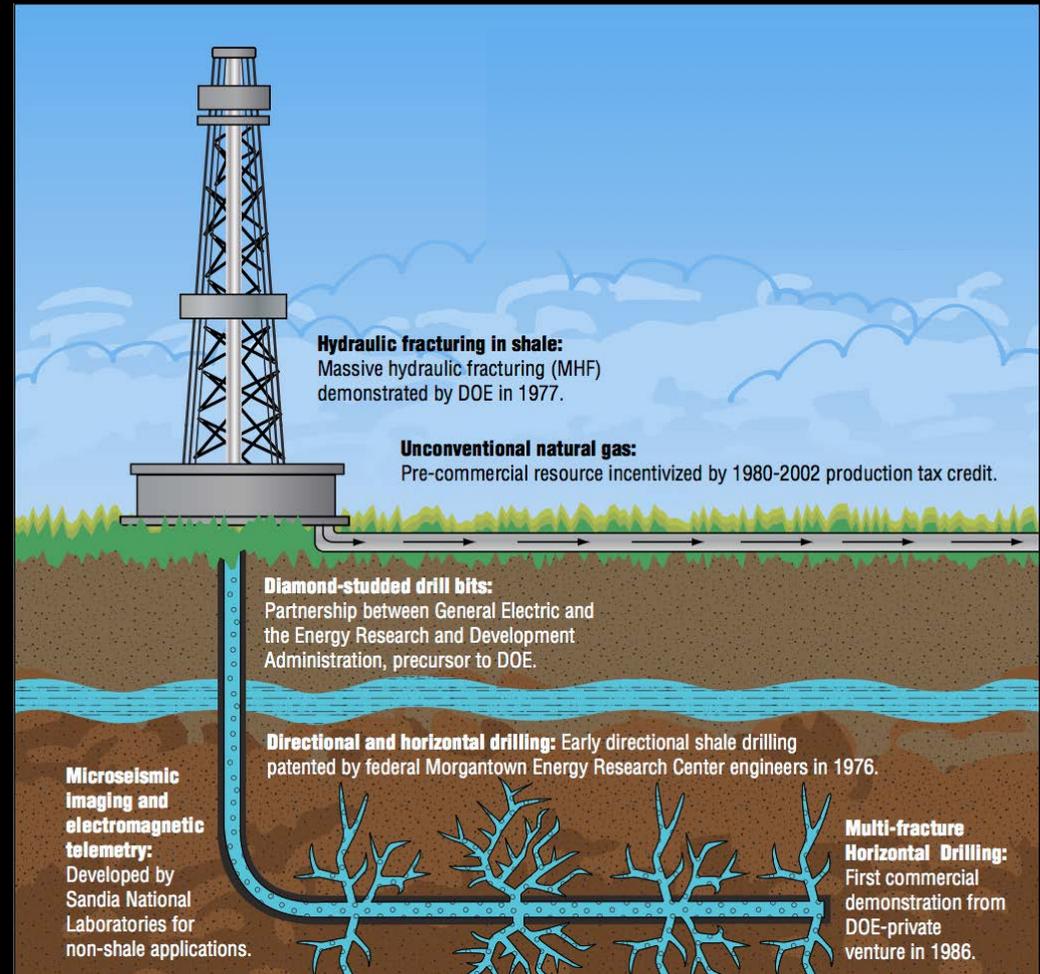


George P. Mitchell

Mitchell Energy

Investments Leading to Gas Boom

- 1970s Diamond-studded drillbits (DOE/GE)
- 1976 Directional/horizontal drilling (NETL-DOE)
- 1977 Massive hydraulic fracturing (DOE)
- 1980s Microseismic imaging (Sandia-DOE)
- 1986 Multi-fracture horizontal drilling (DOE-private)



1980-2002 Production tax credit for unconventional gas

Public-private investments were critical to
the natural gas boom we enjoy today

40 years later

Advanced Research Projects Agency-Energy



Ensuring U.S. leadership in advanced energy technologies



MOVE Program

Methane Opportunities for Vehicular Energy

Mission

Light duty NGVs + home refueling with 5-year payback

Goals

- 3x cheaper gas tanks (\$1500)
- 90% conformable gas tanks
- 10x cheaper compressor (\$500)

Approach

- Low pressure storage (< 500 psi): sorbents
- High pressure storage (3,600 psi): tanks + compressors

Investment

- 2012-2015, \$30M, 13 projects

MOVE Portfolio

Program Goal

Payback less than 5 years for light duty NGVs with conformable tanks and at-home refueling

Compressors

- Liquid piston
- Multi-stage linear piston
- Cryocooled-sorbent
- Dual engine-compressor



Sorbents

- Metal organic frameworks
- Nanovalved
- Containerless tank



Tanks

- Superplastic forming
- 3-D squeeze cast
- Cellular module
- Intestine storage



United Technologies Research Center



Otherlab

Pressure vessels have not changed in
the last 200 years...

until now

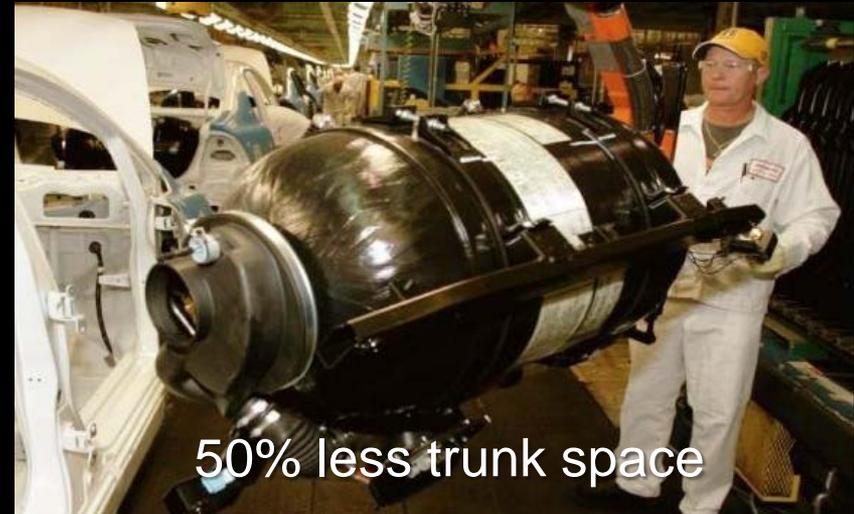


Commercial CNG Tanks

Tank	Type I	Type IV
Material	steel	carbon fiber
Capacity	12 gallon	12 gallon
Weight	490 lb	190 lb
Cost	\$1,700	\$4,300

too heavy

too costly



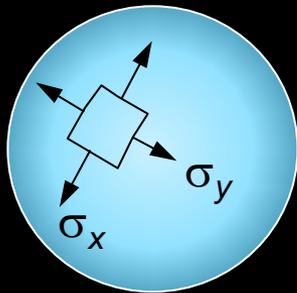
too bulky

Current options too heavy, too costly, too bulky

Thinking Differently About the Problem

How do we use every atom to its maximum?

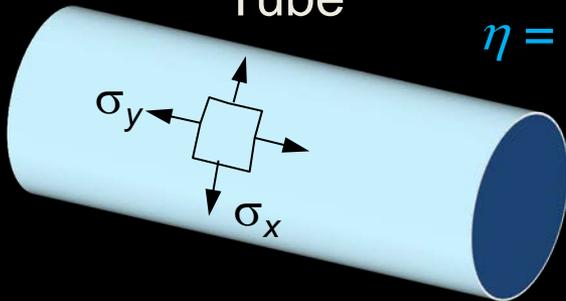
Sphere



$$\eta = 67\%$$

$$\sigma_x = \sigma_y, \sigma_z = 0$$

Tube

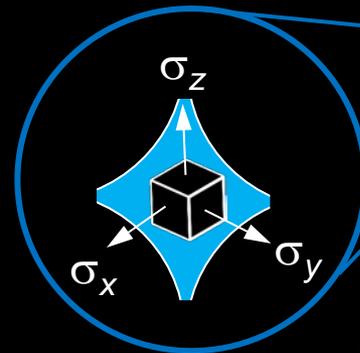


$$\eta = 50\%$$

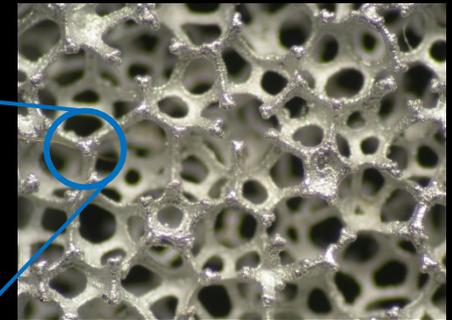
$$\sigma_x = 2\sigma_y, \sigma_z = 0$$

Internal Struts (Foams)

$$\eta = 100\%$$



$$\sigma_x = \sigma_y = \sigma_z$$



η = structural material efficiency

Tank Challenge

Now

heavy, expensive, and **cylindrical**



3600 psi load carried by
Tension

Need

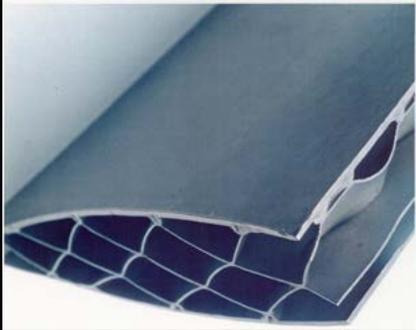
lightweight, low cost, and **conformable**



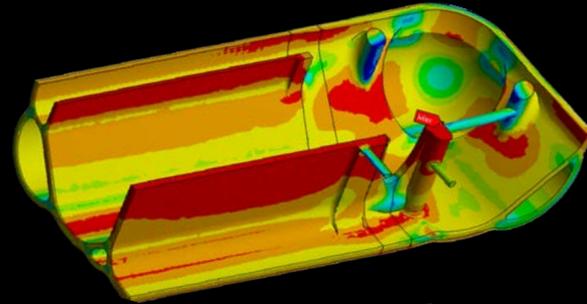
15 psi load carried by
Torque

MOVE Tank Projects

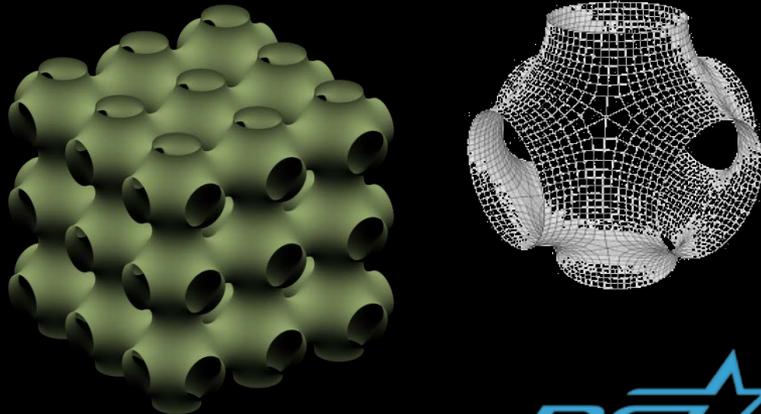
Superplastic-Formed Tanks



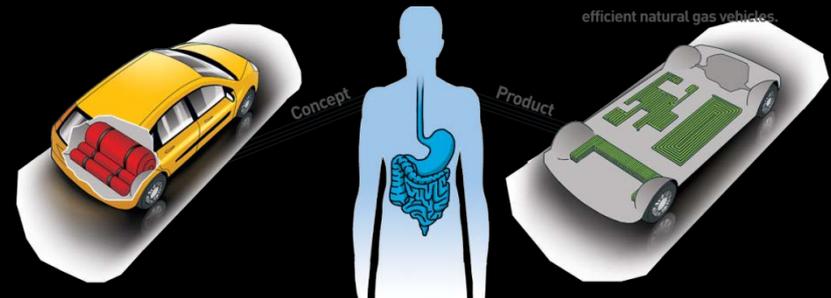
Modular Cell Design



Squeeze Cast 3-D Tanks



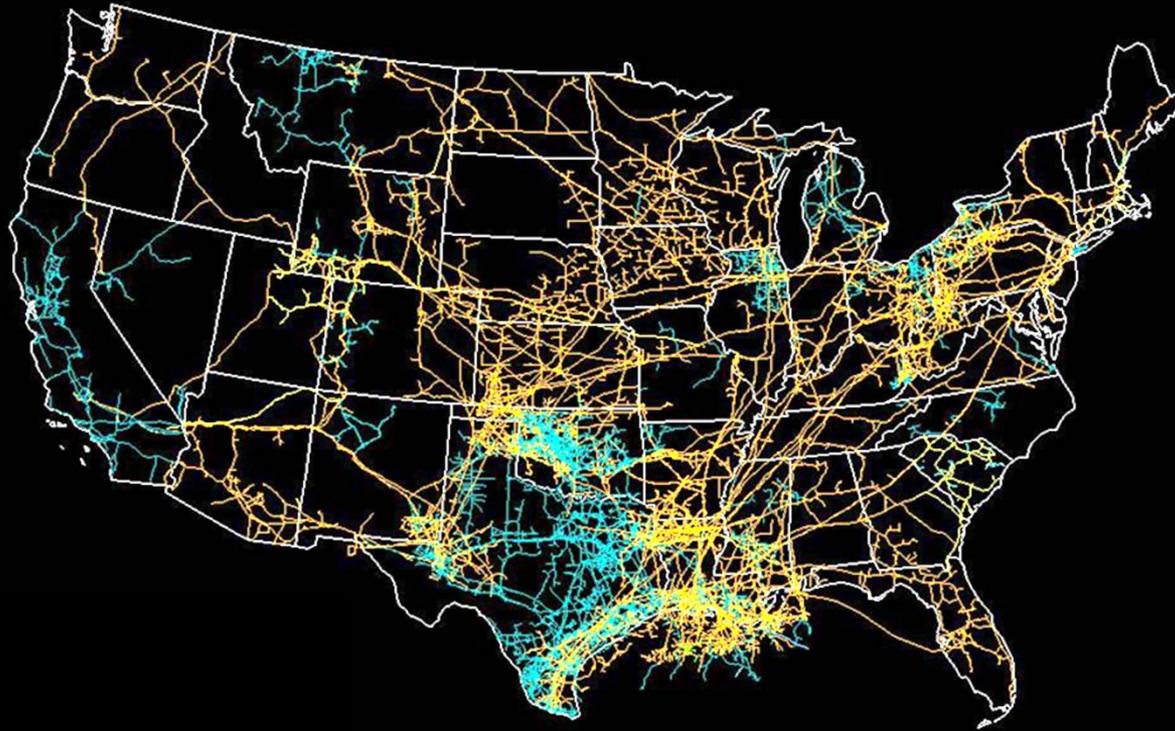
Intestine Tube Storage



What if we could refuel at home?

U.S. Natural Gas Infrastructure

2009 U.S. Natural Gas Pipelines



60 million U.S. homes already use natural gas

Commercial At-Home Refueling Systems

Phill - BRC FuelMaker

- Cost = \$3800 retail + \$1000 install
- Fill rate = 0.4 gge/h (16 mi/h)
- Life = 6000 h (~\$1.50/gge CapEx)
- U.S. sales = 1400 units



Compressor Challenge

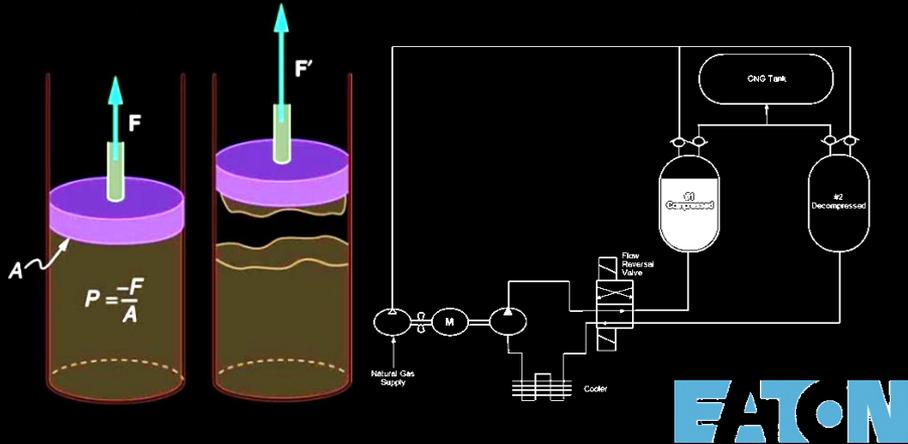
Component	Now	Need
At-home Refueling	\$ 5500	\$ 2000
On-board Storage	\$ 3500	\$ 1500
Balance of System	\$ 3500	\$ 1000
Total	\$12500	\$ 4500
Simple Payback	13 y	5 y

At-Home Refueler Target

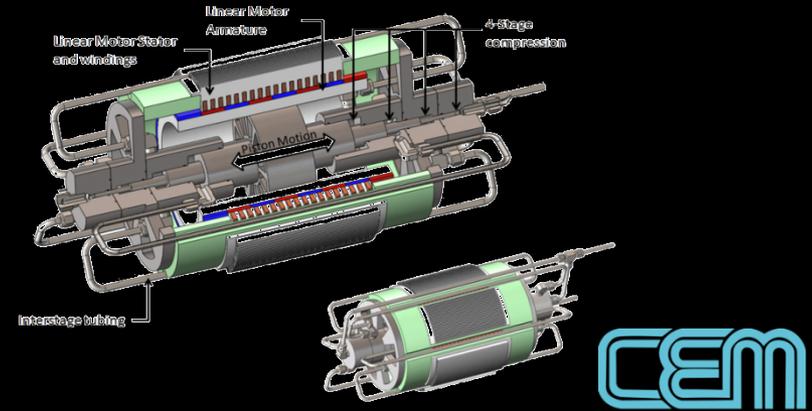
\$1000 Refueler + \$1000 Installation = \$2000 Total

MOVE Compressor Projects

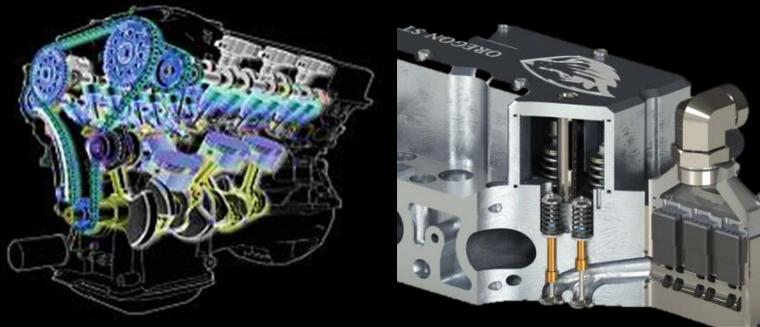
Liquid Piston



Multi-Stage Linear Piston



Dual Function Engine

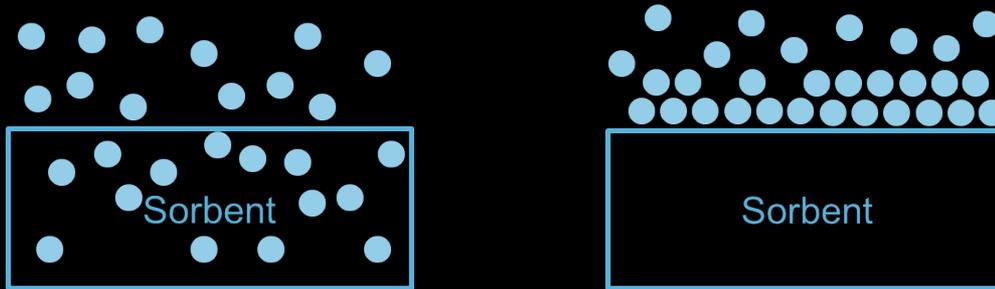


Chilled-Adsorbent System



What if we didn't need high pressure
to store natural gas?

What are adsorbents?



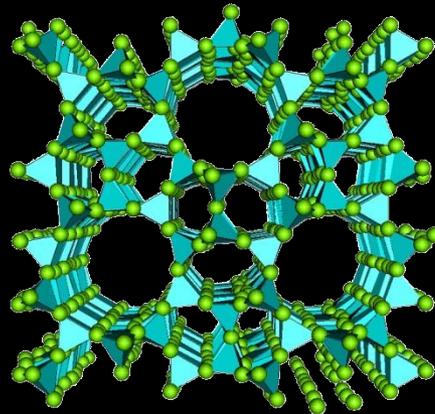
Absorption

Adsorption



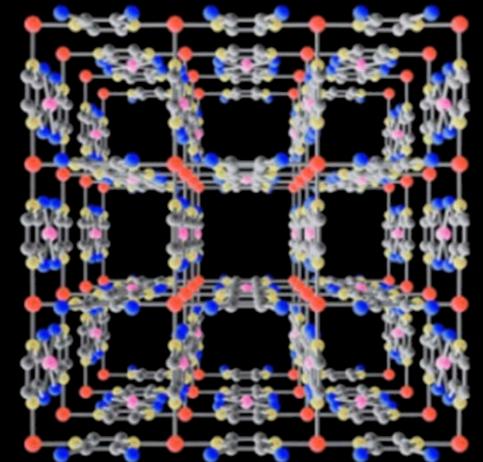
Activated Carbons

Various (pre-historic)



Zeolites

Baron Cronstedt (1756)



Metal Organic Frameworks

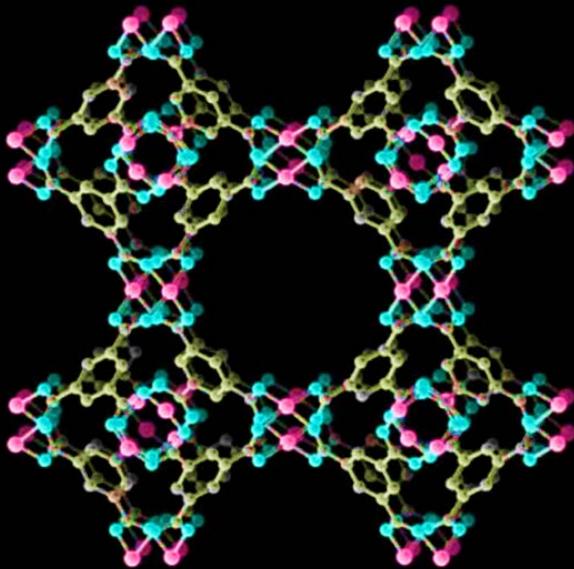
Omar Yaghi (1995)

Sorbent Challenge

Sorbent (500 psi) = CNG (3600 psi)

Cost < \$10/kg

HKUST-1



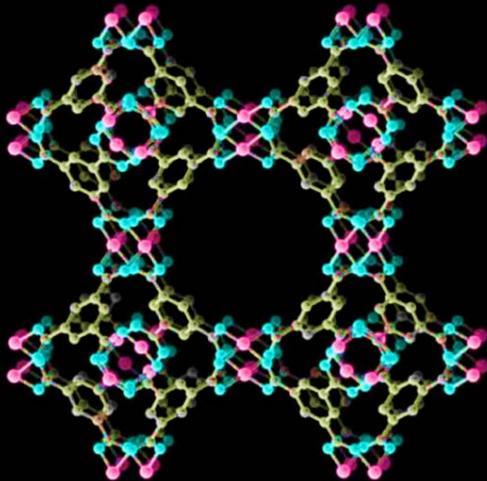
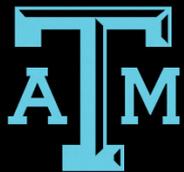
HKUST-1 (500 psi) = 8.1 MJ/L*
CNG (3600 psi) = 9.2 MJ/L

*total capacity

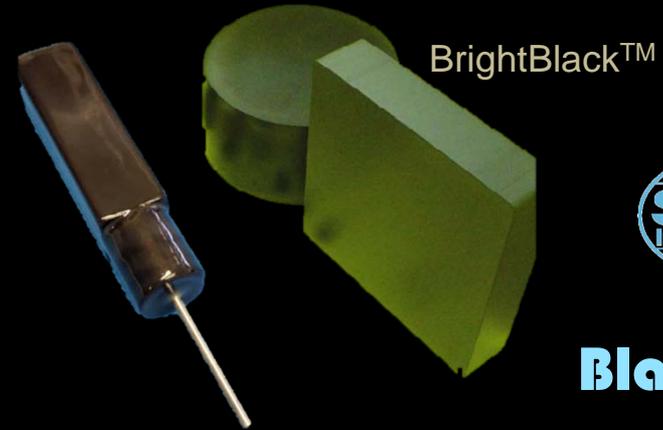
Fundamental challenges: cost, packing, working capacity

MOVE Sorbent Projects

Metal Organic Frameworks

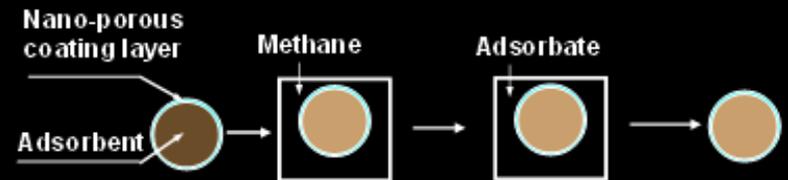


Containerless Storage



BlackPak

Nanovalves



MOVE Technology to Market

13 projects
4 new companies
2 more anticipated



Take Aways

1. Economics alone will not drive consumer adoption
2. NGVs must have comparable performance **plus** added benefit
3. Convenient, low-cost home refueling could be the game changer
4. New technology needs near-term markets to survive slow adoption times

Thank You!

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