arpa·e energy innovation summit

Capturing America's Natural Gas

Moderator: Dr. Ramon Gonzalez, ARPA-E

Dr. Dane Boysen, ARPA-E

Dr. Ashwin Salvi, Fellow, ARPA-E

Dr. Bryan Willson, Program Director, ARPA-E

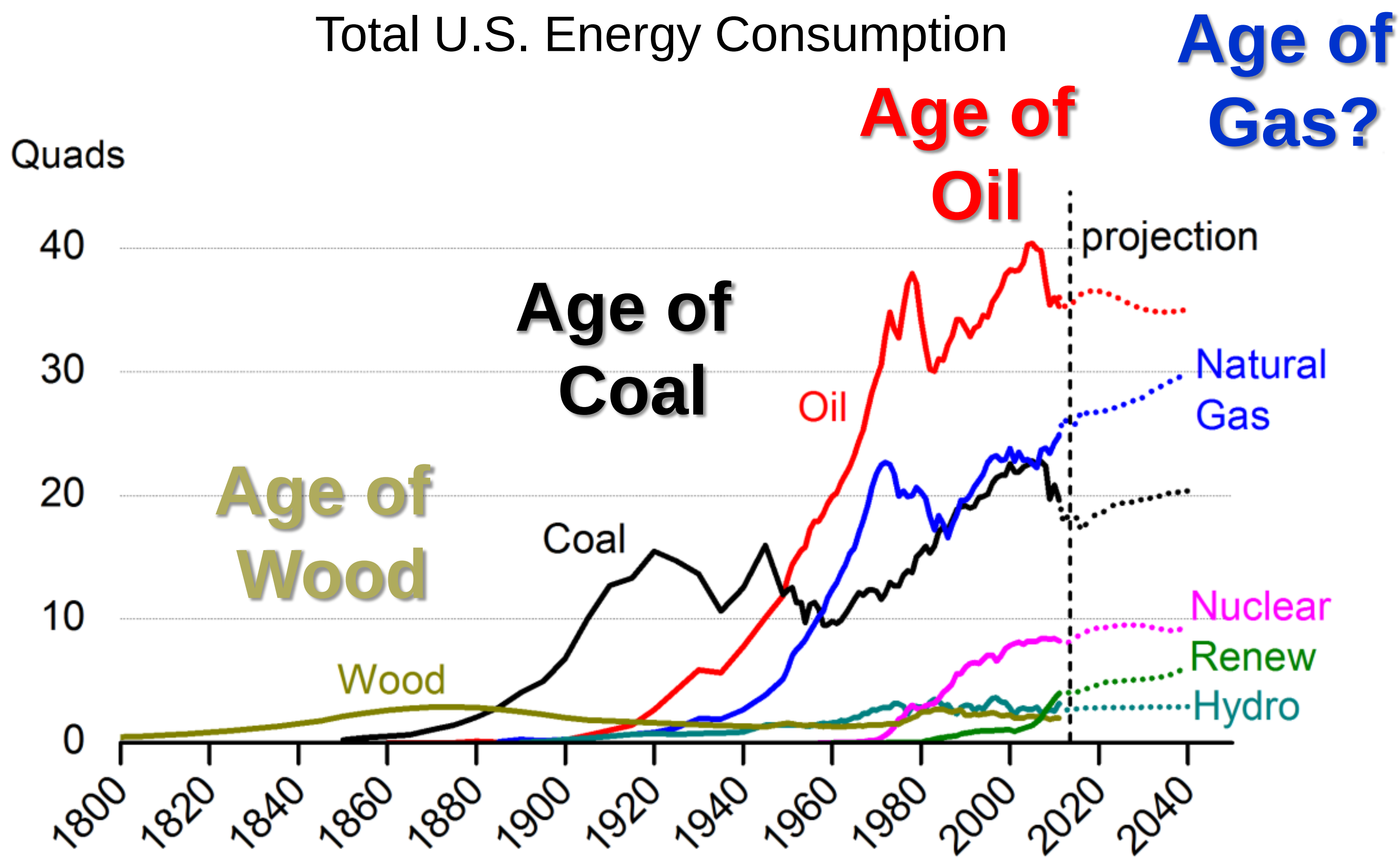
Natural Gas Session

I. Background
- history, current status — Bryan Willson

II. Risks & Challenges
- environmental, economic — Bryan Willson

III. Opportunities
- transportation, heat & power — Dane Boysen
- conversion, renewable gas — Ramon Gonzalez
- new areas, emerging ideas — Ashwin Salvi

Increasing Role of Natural Gas

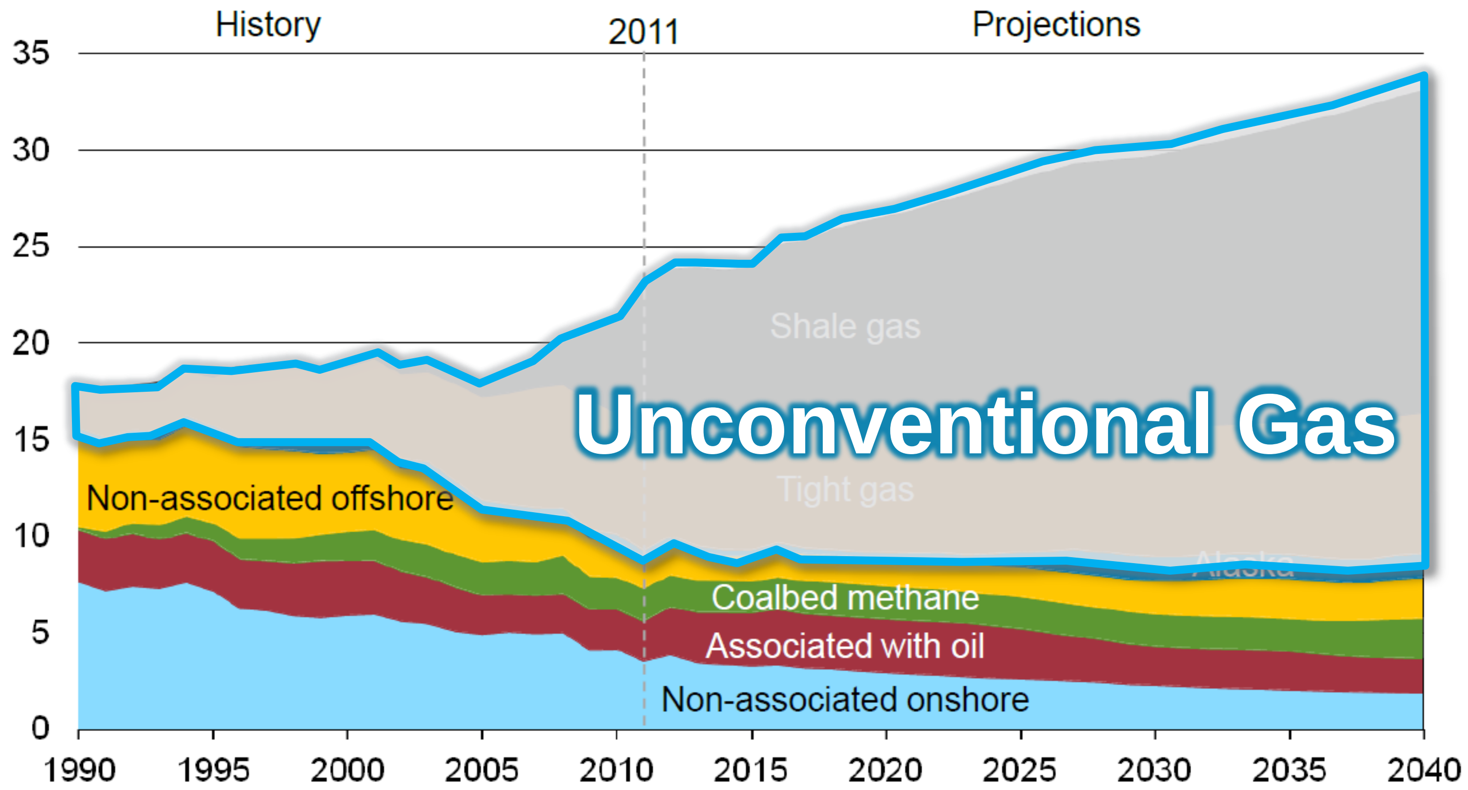


Source: U.S. Energy Information Administration Annual Energy Review, Tables 1.2, 10.1, and E1.

Driven by Unconventional Gas

Enabled by horizontal drilling & hydraulic fracturing

U.S. Dry Natural Gas Production

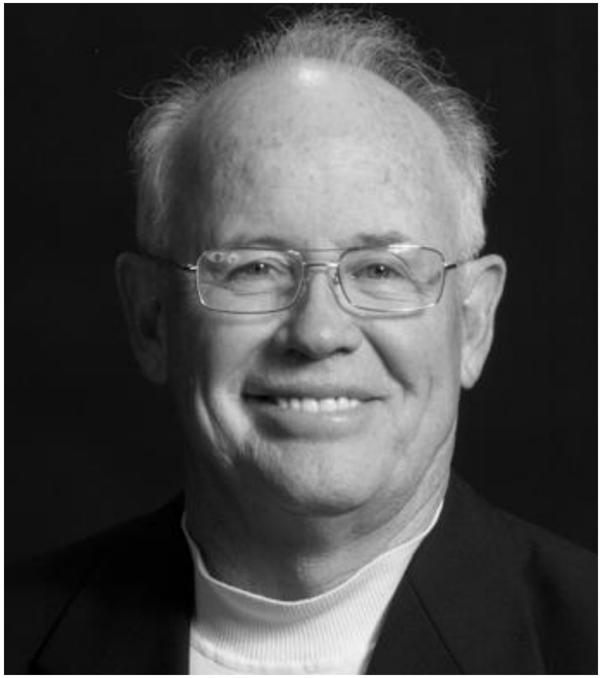


Source: EIA, Annual Energy Outlook 2013 Early Release

How did this happen?

Horizontal Drilling & Hydraulic Fracturing

35+ years from R&D to "disruption"



Alex Crawley

Energy R&D Administration

George P. Mitchell

Mitchell Energy

Federal Investments Leading to Gas Boom

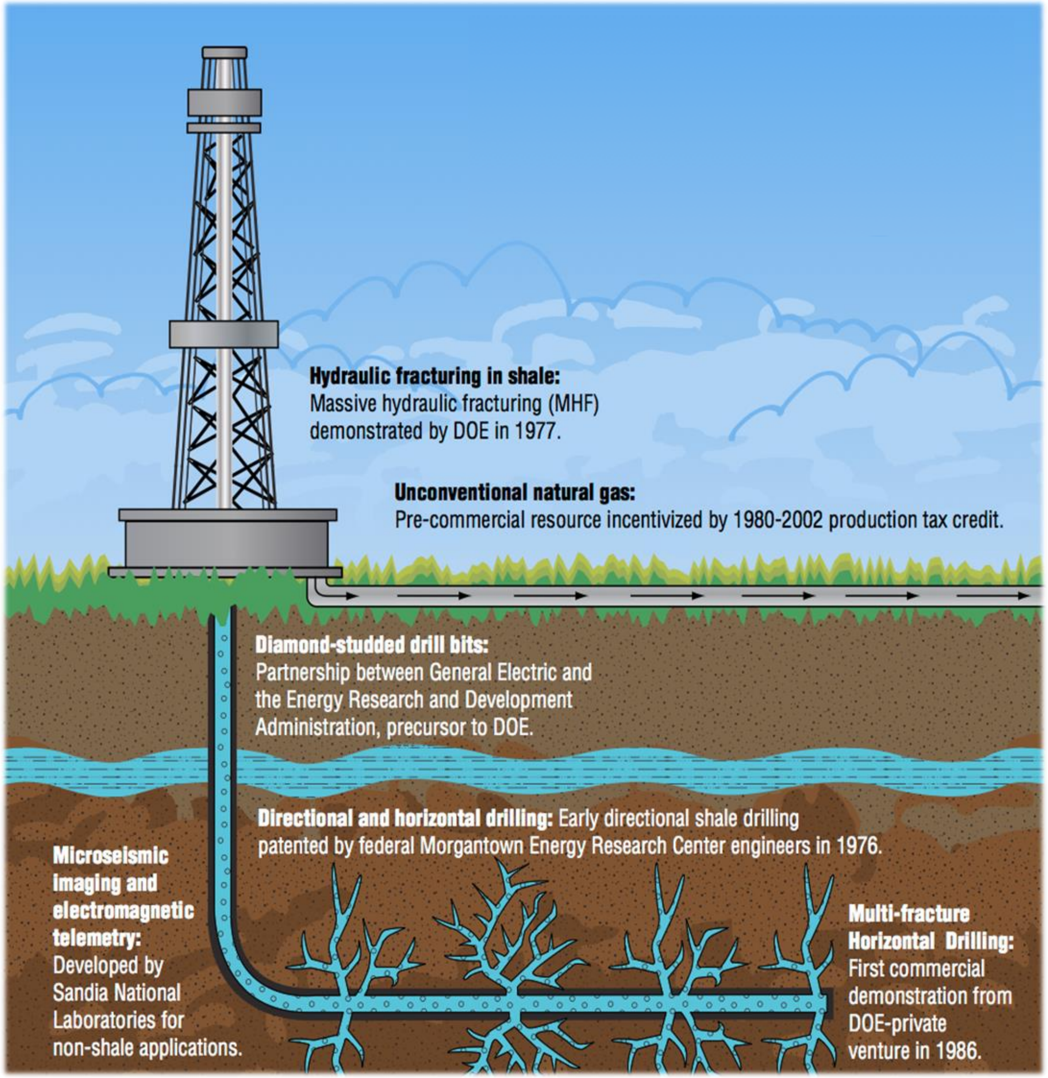
1976 Directional/horizontal drilling (NETL-DOE)

1977 Massive hydraulic fracturing (DOE)

1980s Microseismic imaging (Sandia-DOE)

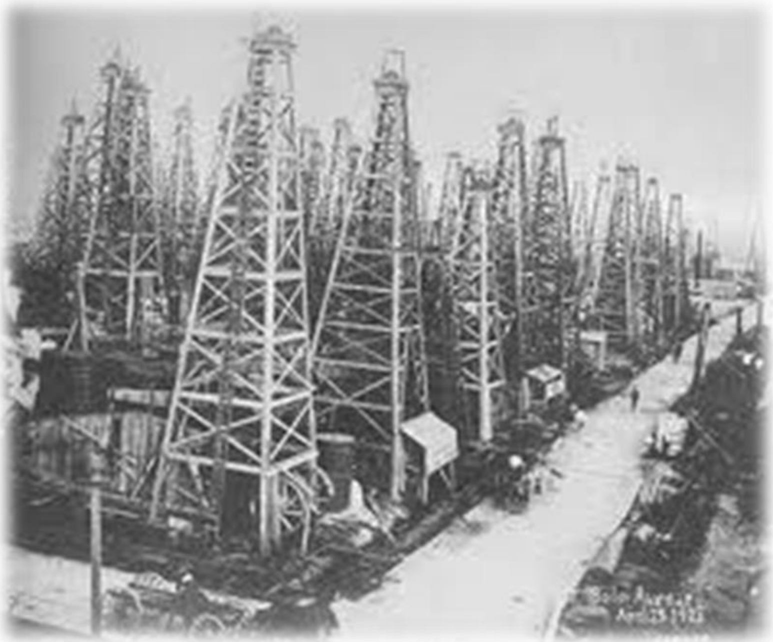
1986 Multi-fracture horizontal drilling (DOE-private)

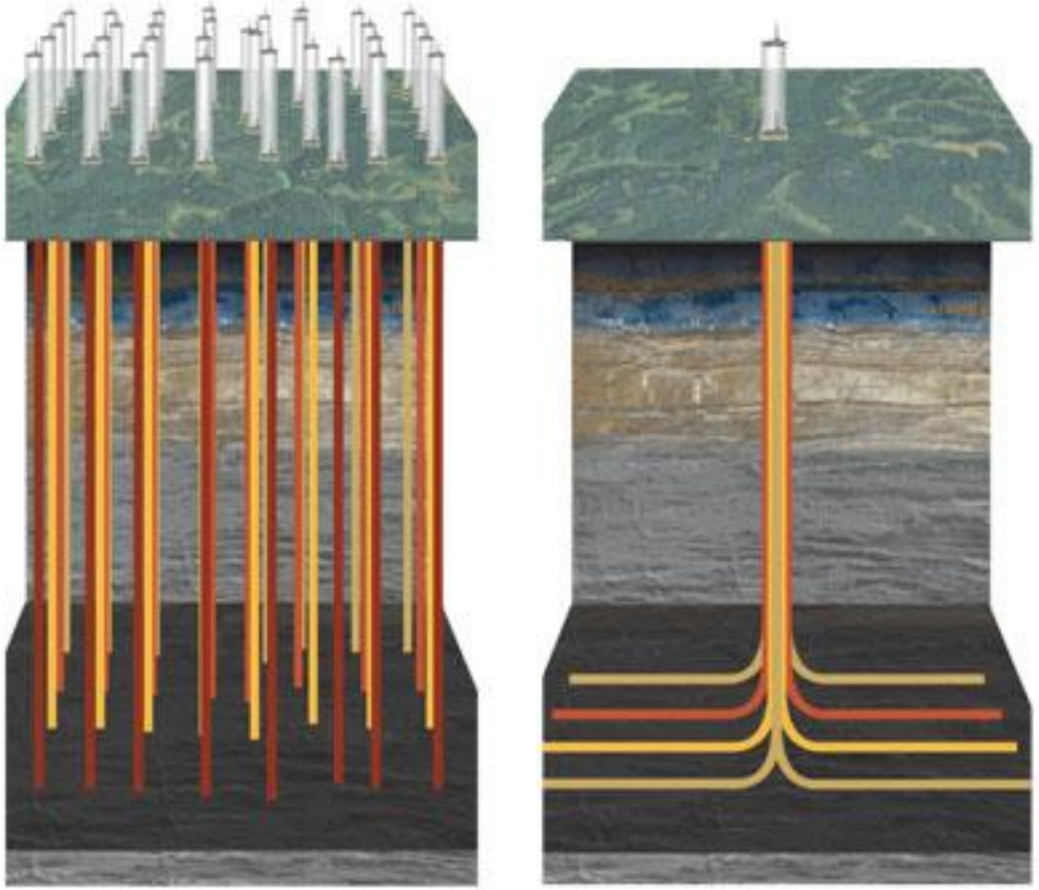
1980 Production tax credit unconventional gas, ended 2002



Source: A Trembath, J Jenkins, T Nordhaus, M Shellenberger. *Where the shale gas revolution came from*. Breakthrough Institute. May 2012

Reduced Impact from Multi-Well Pads





32 padsites for 32 wells

1 padsite for 32 wells

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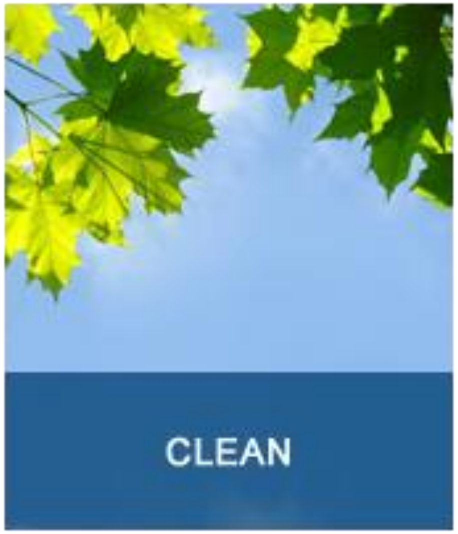
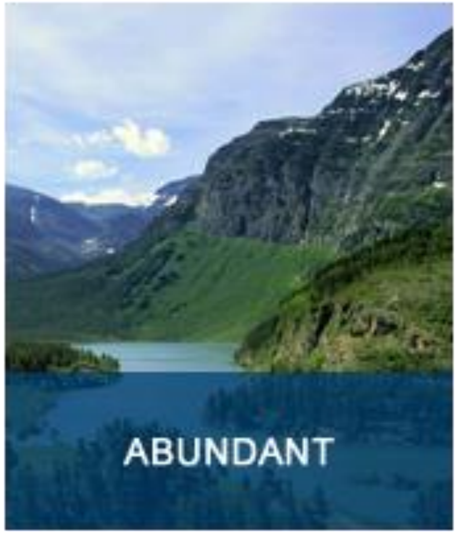
Crisis?

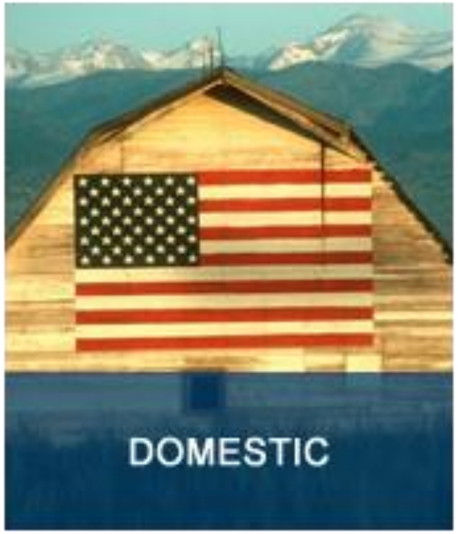

WINNER AUDIENCE AWARD
WINNER Big Sky
WINNER
WINNER GRAND JURY PRIZE 2010 ENVIRONMENTAL FILM FESTIVAL AT YALE
WINNER SUNDANCE FILM FESTIVAL
dimethyl formamide ethanol
ethylene glycol ferrous sulfate
glycerol hydrochloric acid
mercaptoacidic acid methanol
alcohol
maldehyde
polyol
sodium hydroxide
GASLAND


Do Not Drink this Water

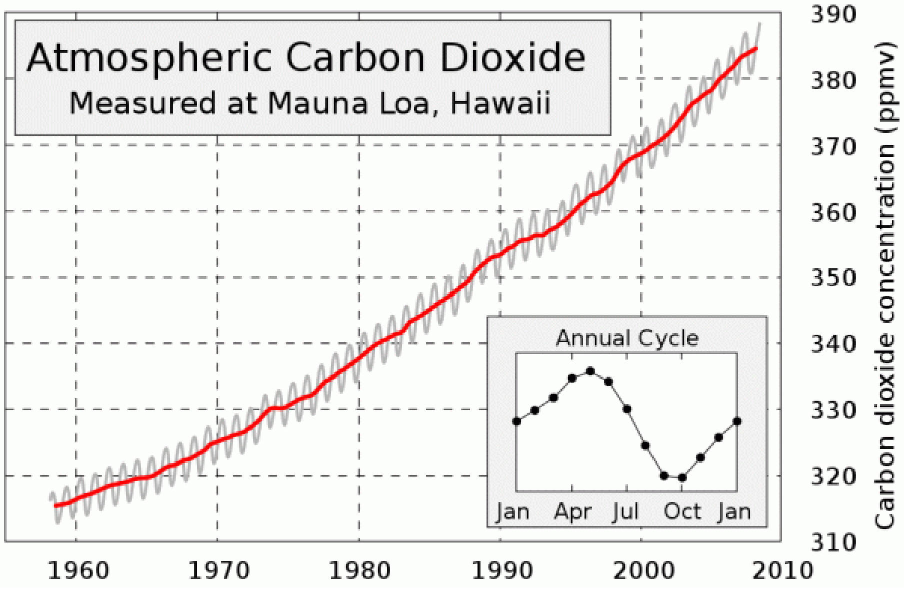
Or Solution?



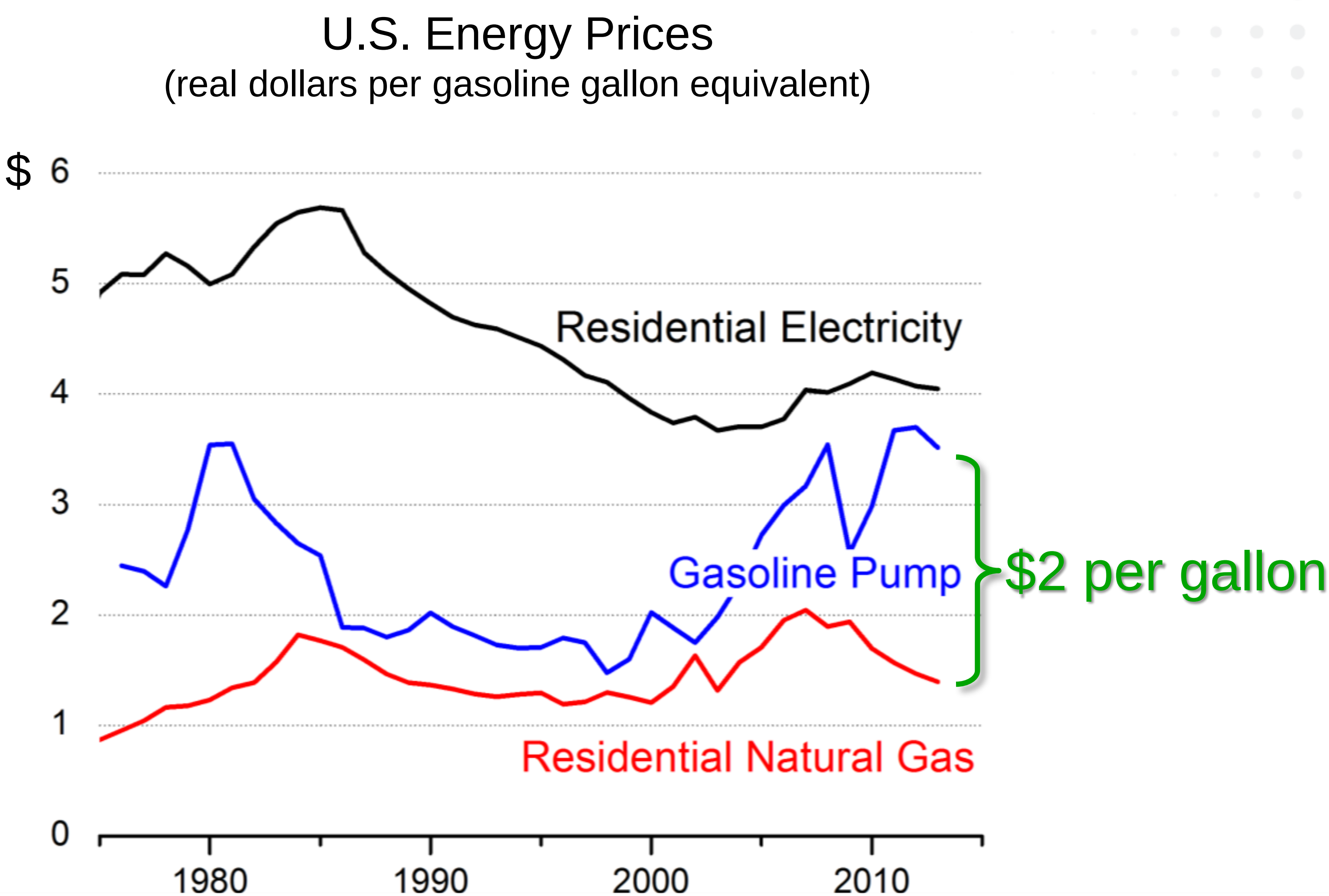




Why Natural Gas?

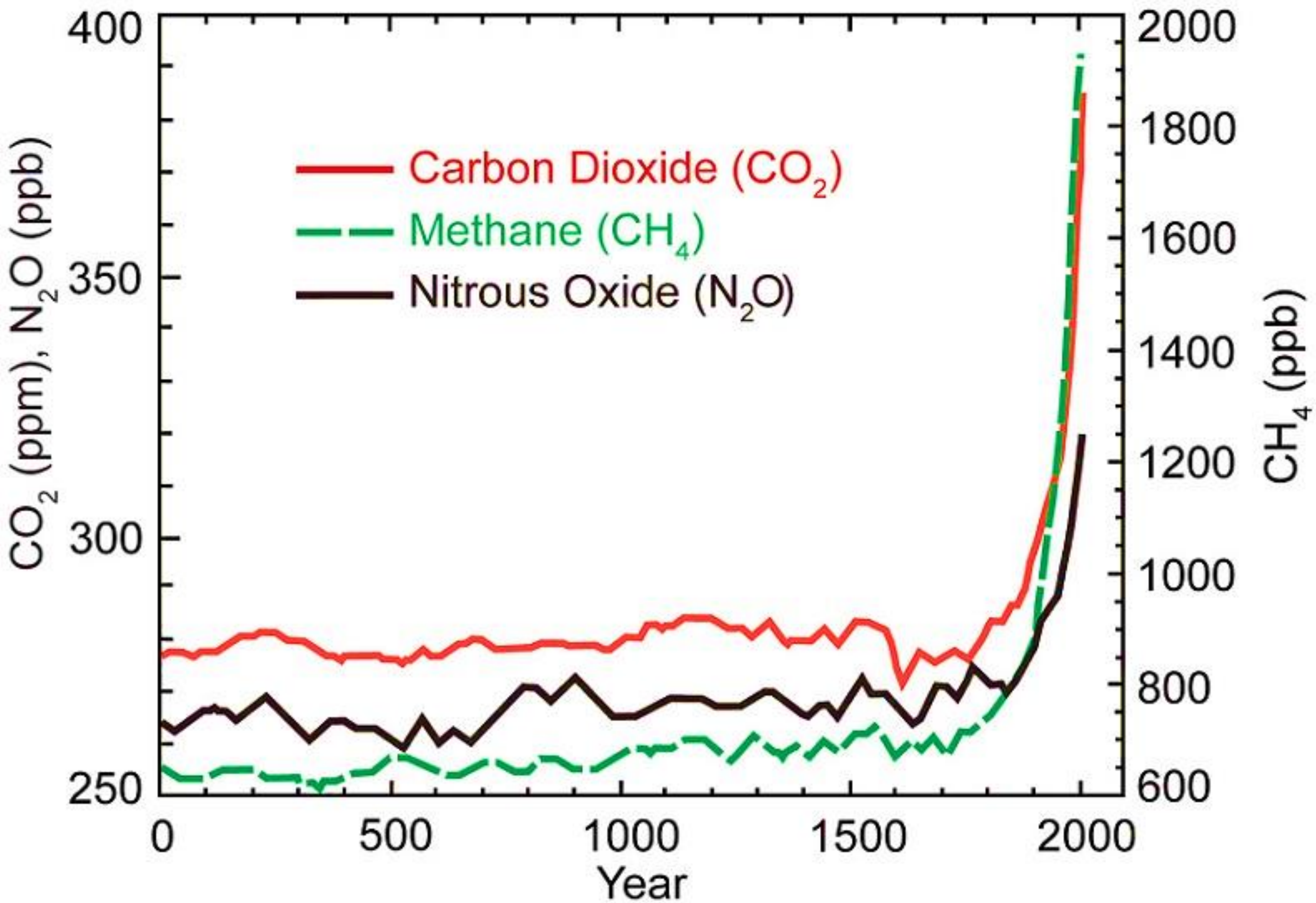


Energy Prices Are Down



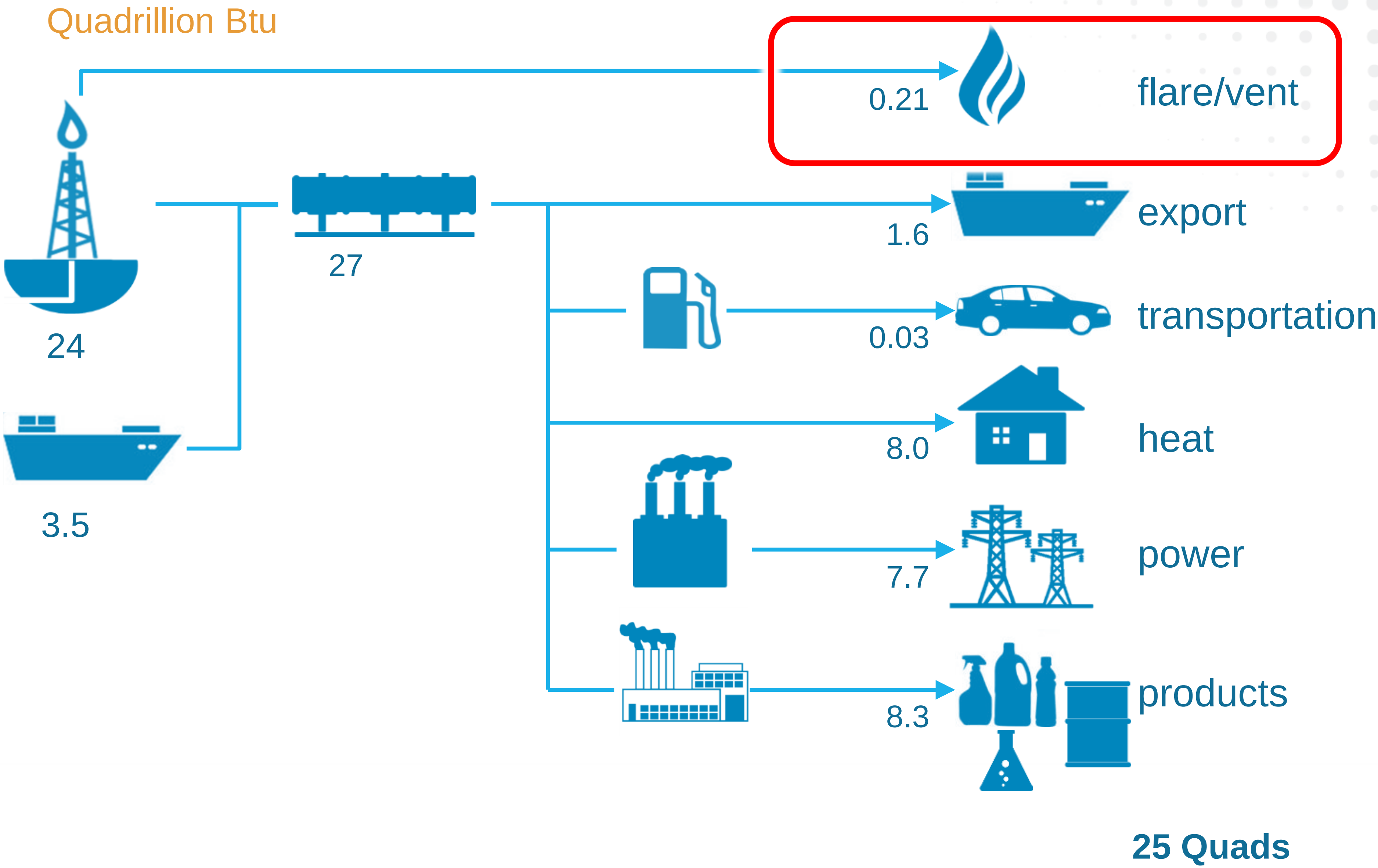
Source: EIA Short-Term Energy Outlook, Short-Term Energy Outlook Real and Nominal Prices, November 2013

But Atmospheric CH_4 Levels Are Rising



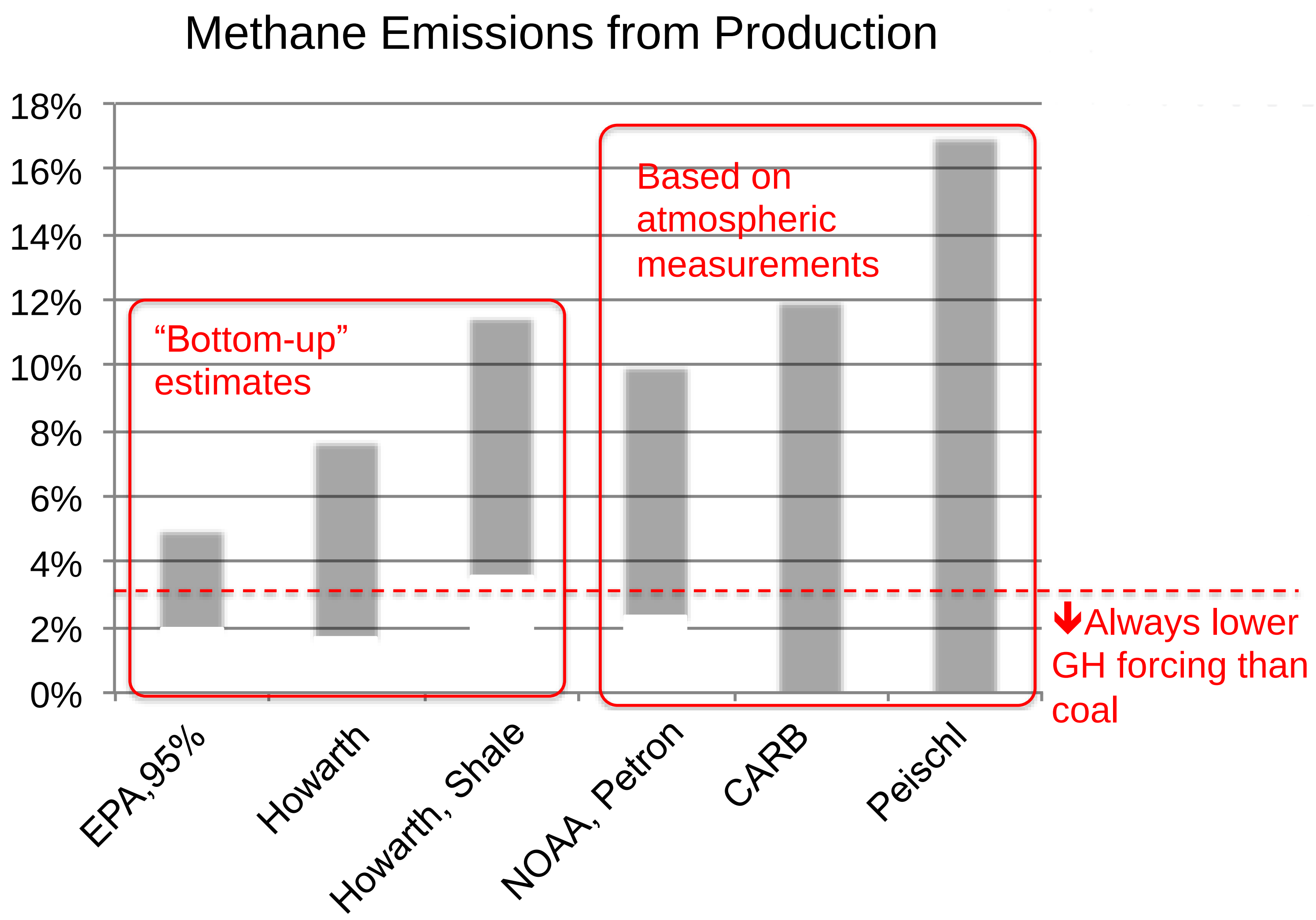
Source: http://www.epa.gov/climatechange/science/causes.html

2011 U.S. Natural Gas Energy Flows



Source: U.S. Energy Information Agency, January, 2014, http://www.eia.gov/

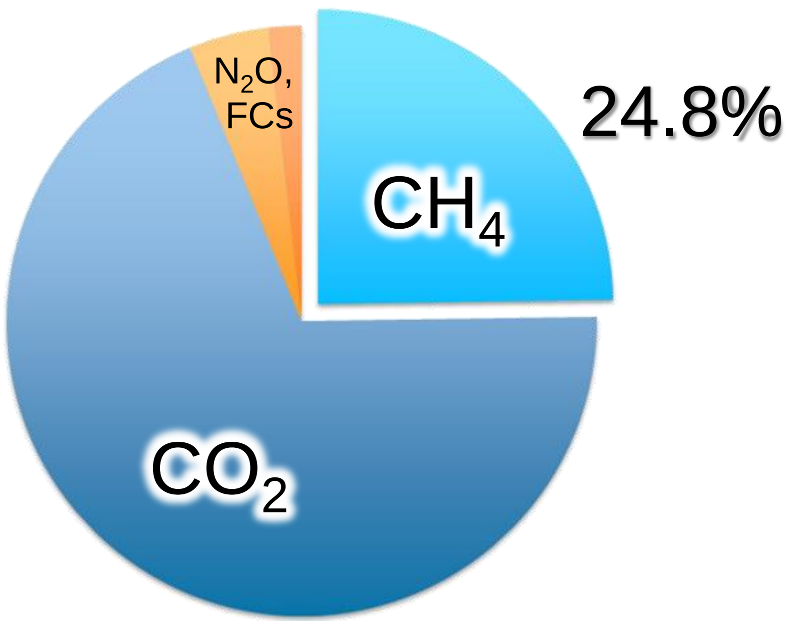
Emissions Uncertainty



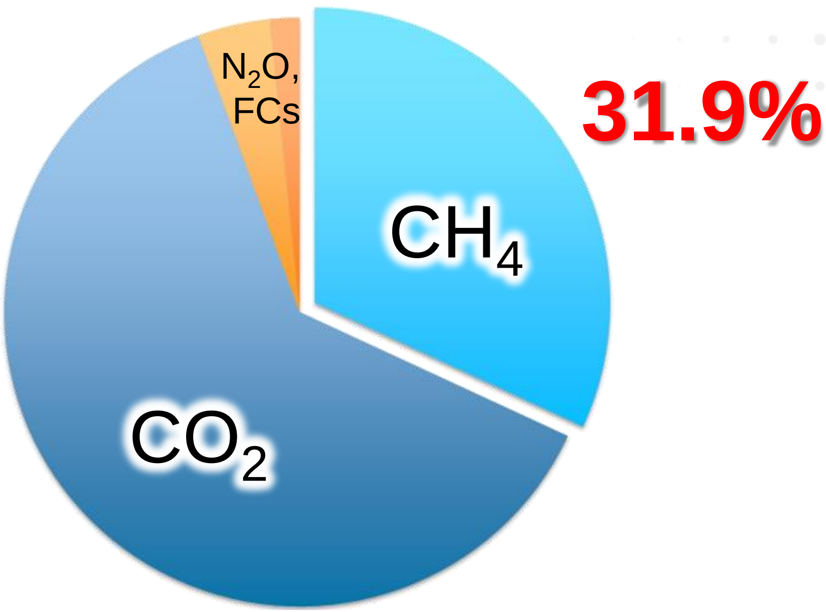
Estimates range from **less than 1%** to **more than10%**

Emissions Impact

IPCC 1995
$GWP_{20} = 72$



IPCC 2013
$GWP_{20} = 86$



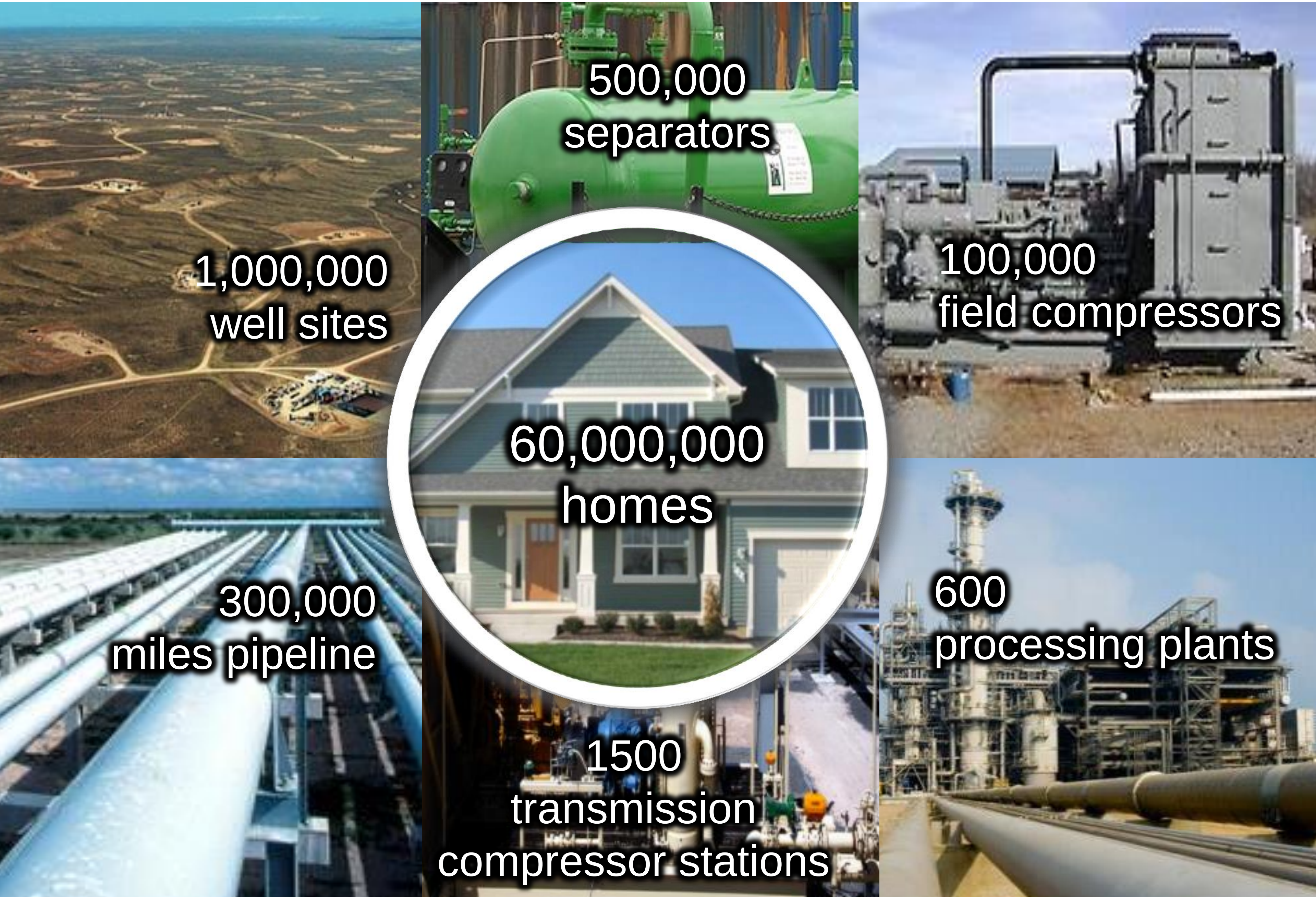
86 ➡ new 20-yr GWP for methane

1.6% ➡ EPA methane leakage estimate

32% ➡ methane impact on global warming

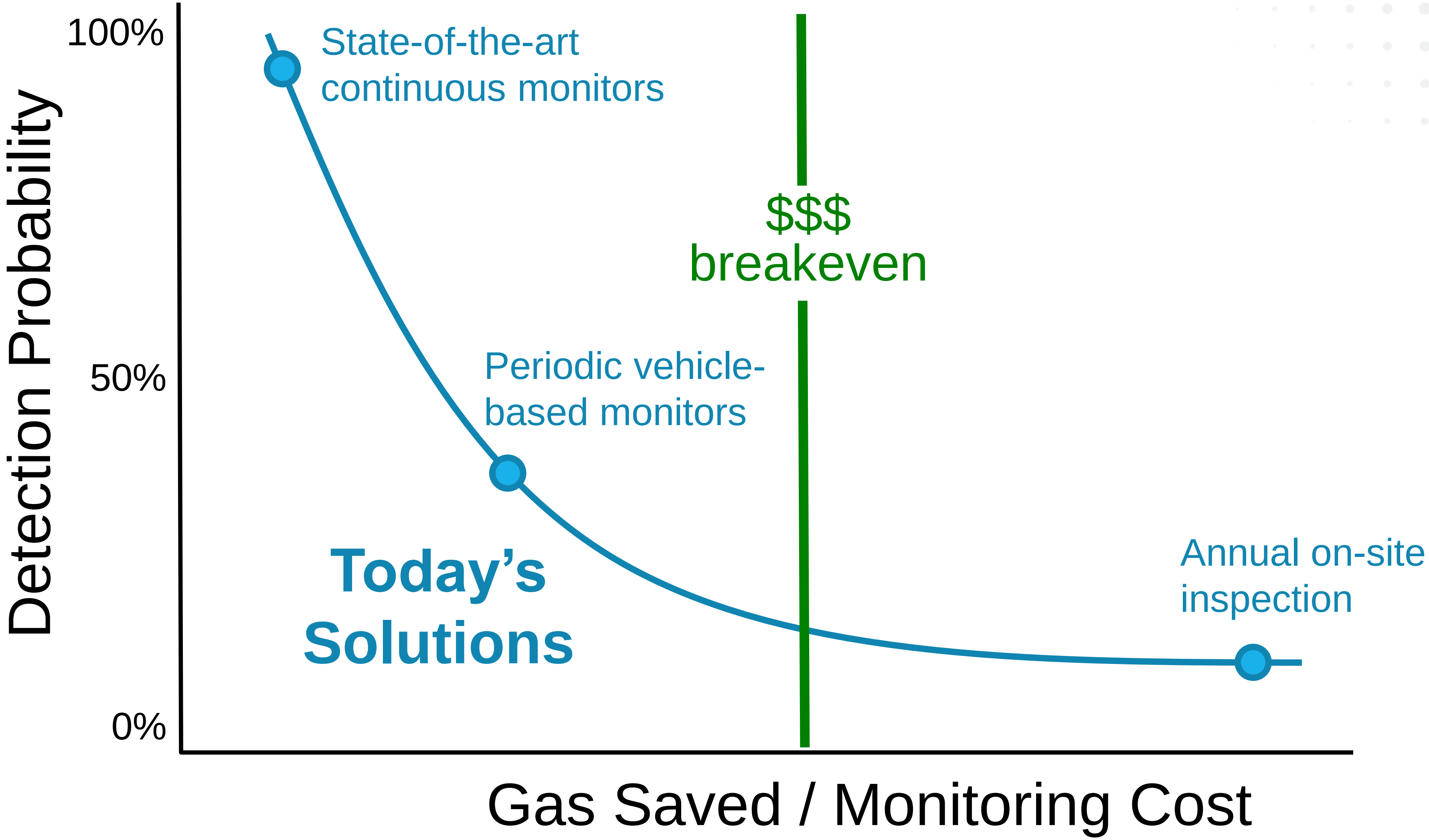
(1) Assumes EPA mid-level rates, (2) IPCC 5[th] Assessment Report, including climate-carbon feedbacks in response to reference gas CO_2, pp 8-58.

U.S. Natural Gas System

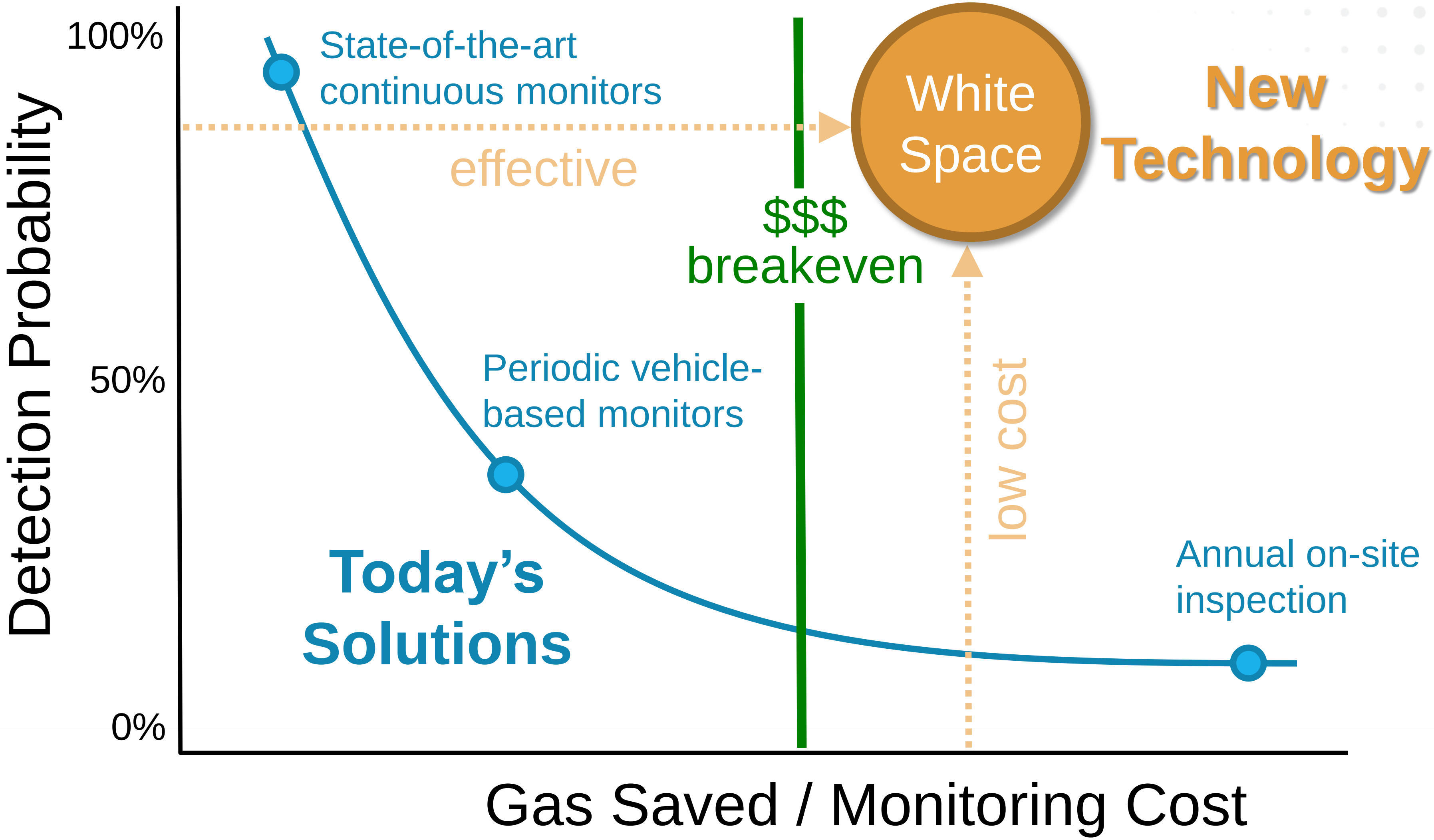


Without measuring methane emissions, we really don’t know how bad the problem is

Today’s Methane Sensing Solutions



Need Effective, Low Cost Methane Sensing



Technology I'm Interested in Discussing

- Lower cost tunable laser diode absorption spectroscopy
  - Including new mid-IR laser technology: QCL, ISB, VCSEL
  - Including new mid-IR non-cryogenic sensors
- Lower cost, higher resolution imaging, particularly with non-cryogenic detectors
- Plasmonic imaging detectors
- Hyperspectral imaging
- LIDAR or laser backscatter detection
- Highly automated deployment from UAVs
- Ground vehicle deployment, particularly from in-use vehicles
- Sensing networks

…or anything else cool related to methane sensing

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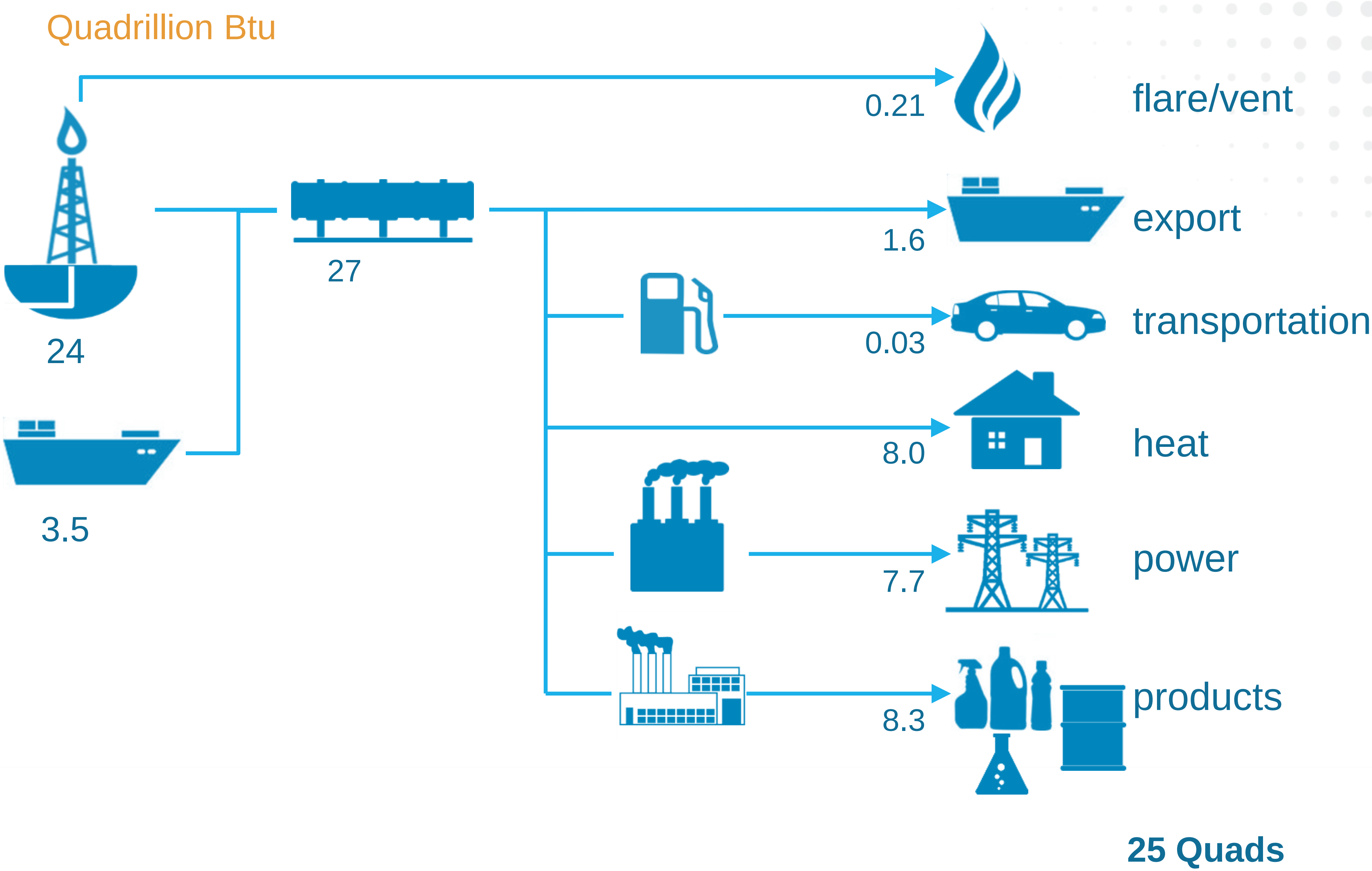
We have a lot of cheap natural gas,

but what can we do with it?

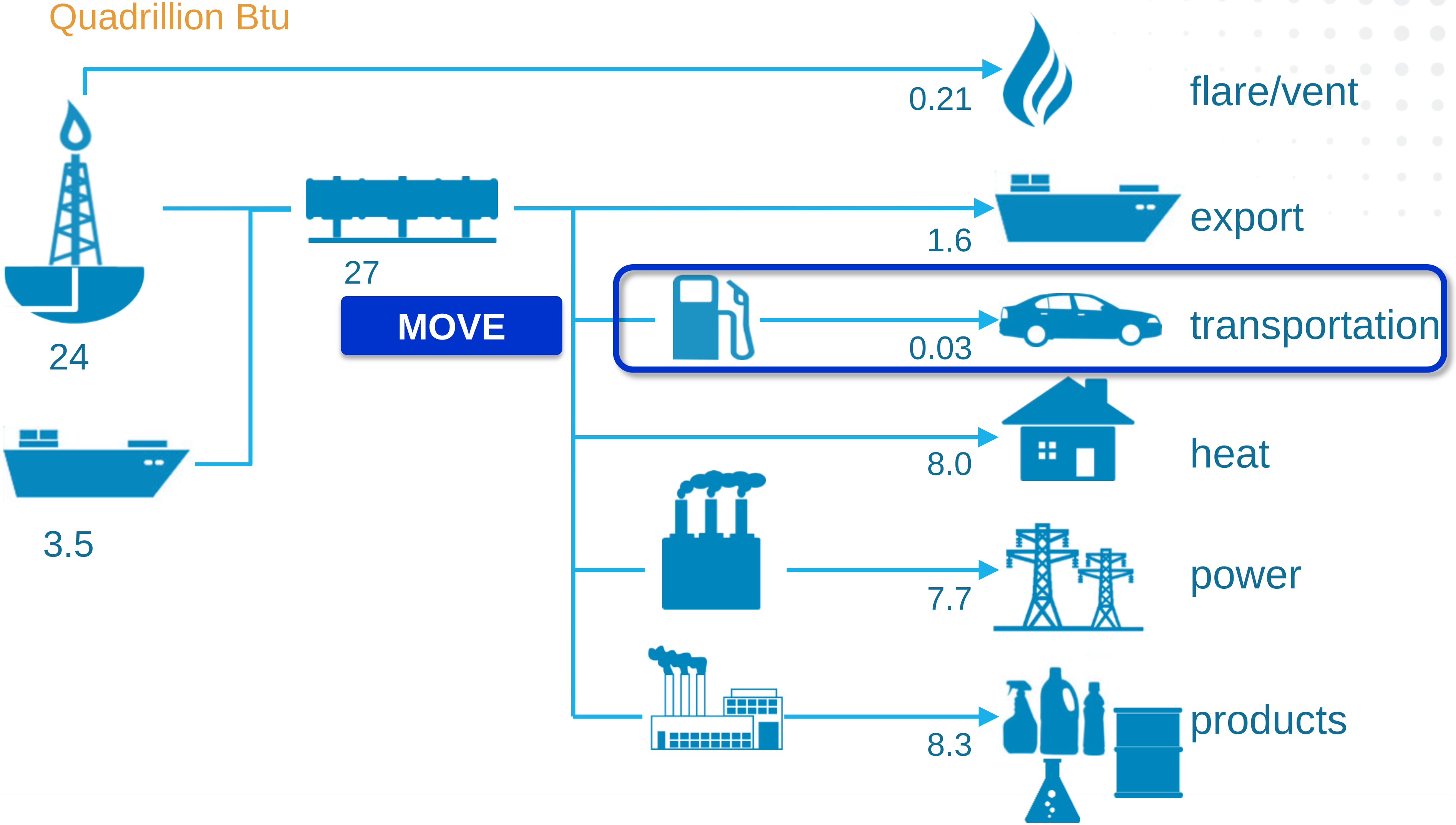
2011 U.S. Natural Gas Energy Flows



Source: U.S. Energy Information Agency, January, 2014, http://www.eia.gov/

2011 U.S. Natural Gas Energy Flows

Quadrillion Btu



25 Quads

Source: U.S. Energy Information Agency, January, 2014, http://www.eia.gov/

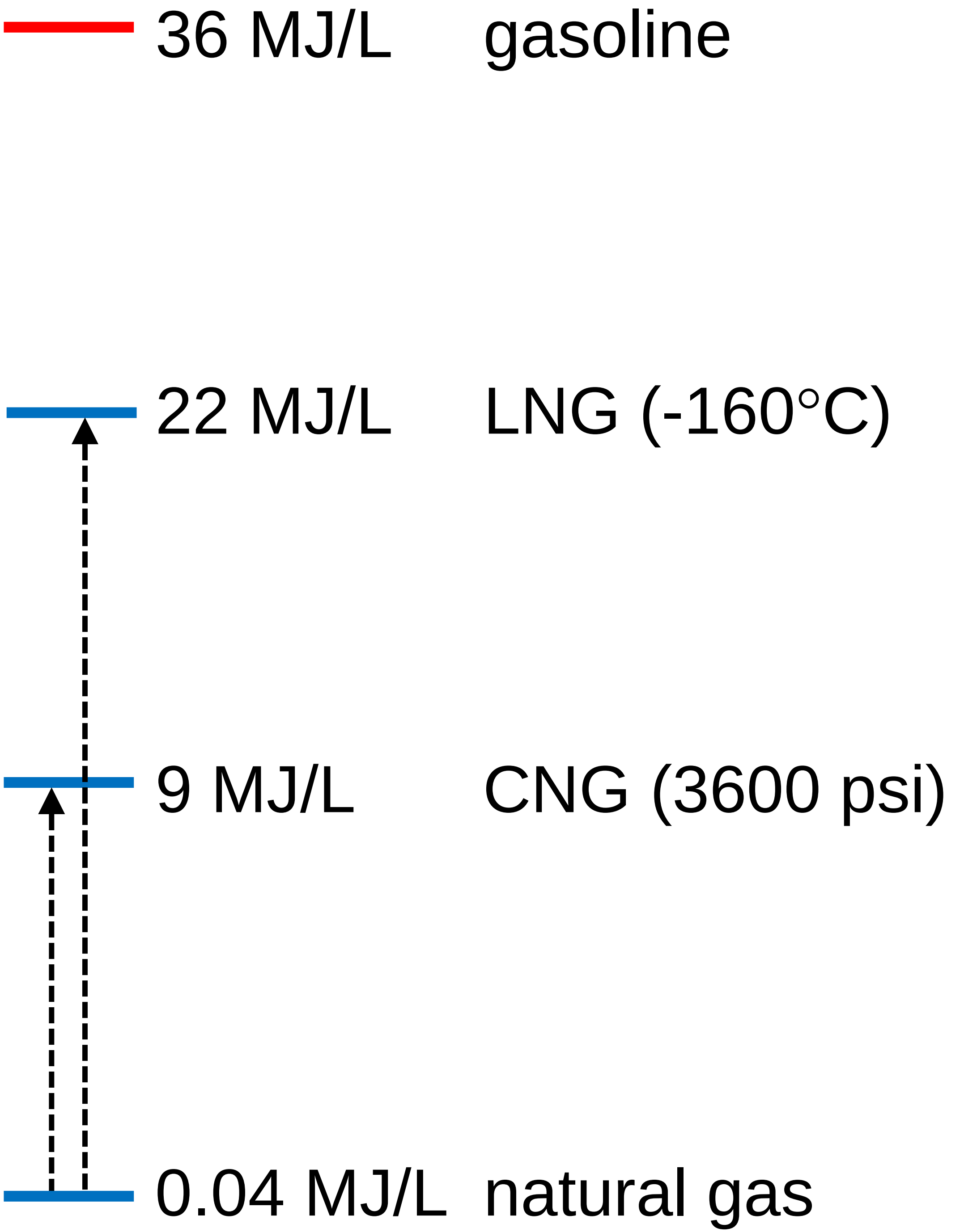
Fact is, natural gas is a poor transportation fuel

What makes a
good transportation fuel?

energy content per unit volume

Gasoline

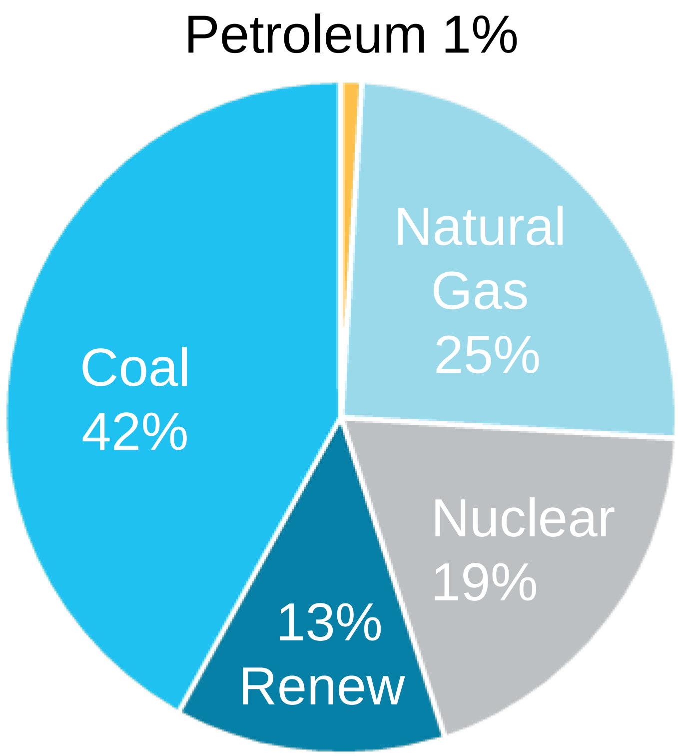
10 gallons per minute = 20 megawatts


36 MJ/L
gasoline
22 MJ/L
LNG (-160°C)
9 MJ/L
CNG (3600 psi)
0.04 MJ/L
natural gas

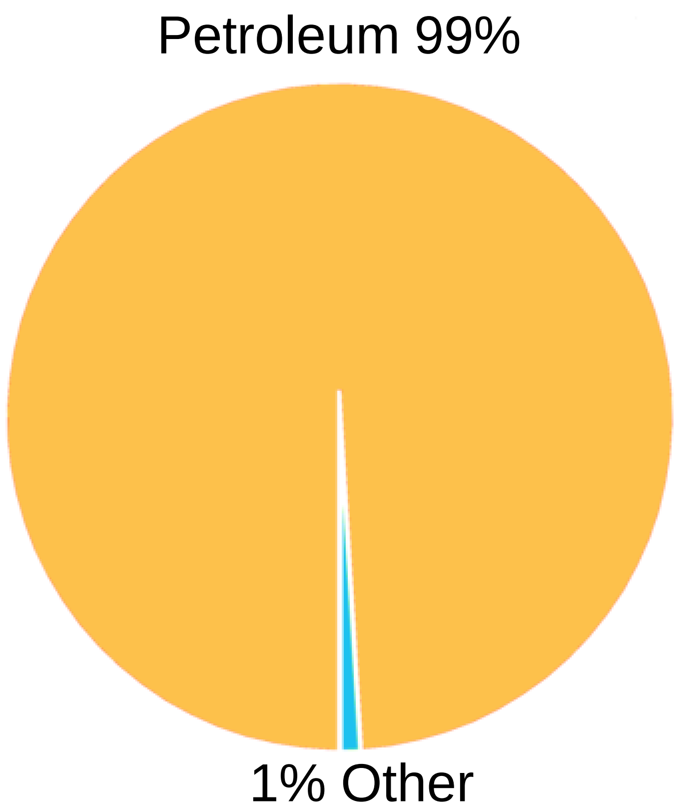
If natural gas is such a terrible transportation fuel, why do we want to put it into vehicles?

Diversification = Energy Security

U.S. Electric Power



U.S. Transportation



[1] www.bts.gov/publications/national_transportation_statistics/html/table_04_04.htm
[2] www.eia.gov/energy_in_briefrenewable_electricity.cfm

Why don’t we have more natural gas light duty vehicles?

Barriers to Natural Gas Vehicles

Where the gas station?

- 632 CNG stations
- 150,000 gasoline

#1 No Infrastructure

Can I put my bag in the trunk?

- 50% less trunk space
- $4000 for tank

#2 Costly, Bulky Tanks

MOVE Program

Methane Opportunities for Vehicular Energy

DE-FOA-0000672, CFDA No. 81.135

Mission

Light duty natural gas vehicles and home refueler with 5-year payback

Program

Funding: $30.0M

Period: 2012-2015

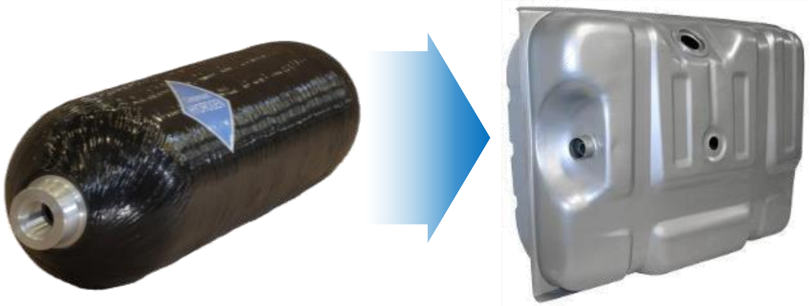
Projects: 13

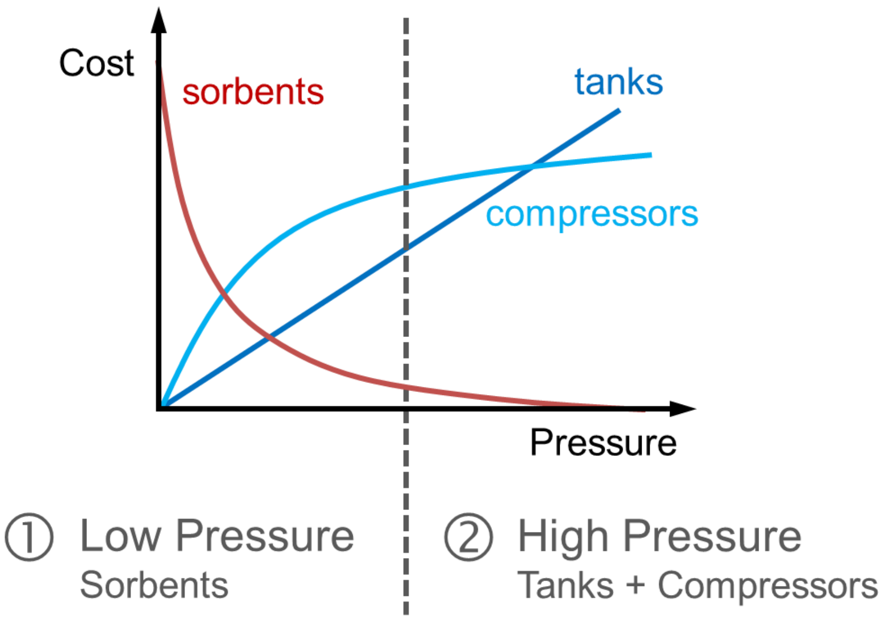
Program Director: Dane Boysen

Contact: dane.boysen@doe.gov

Objectives

- 3x cheaper tanks ($1500)
- 90% conformable gas tanks
- 10x cheaper home refueler ($500)





MOVE Portfolio

DE-FOA-0000672, CFDA No. 81.135

Conformal Tanks

Otherlab

Pacific Northwest NATIONAL LABORATORY

United Technologies Research Center

REL

Adsorbent Storage

Ford

ATM

gti

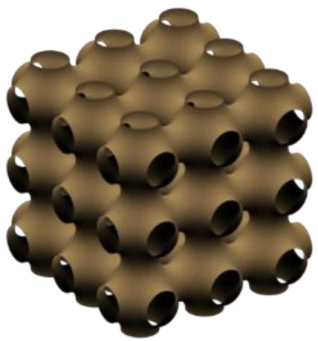
SRI International

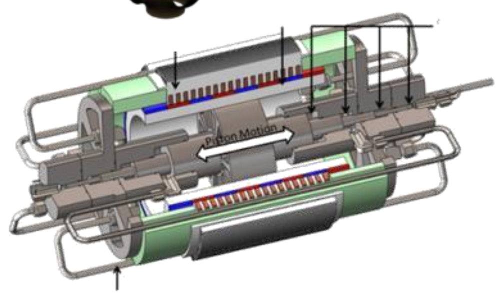
Home Refuelers

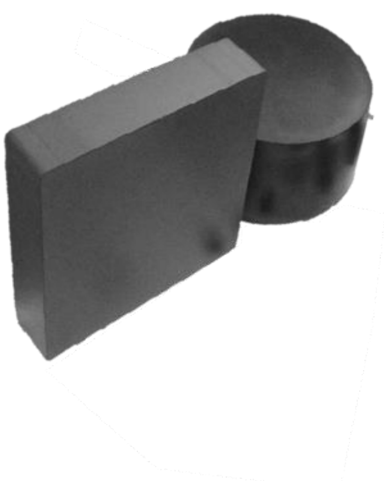
CEM

OSU Oregon State UNIVERSITY

EATON

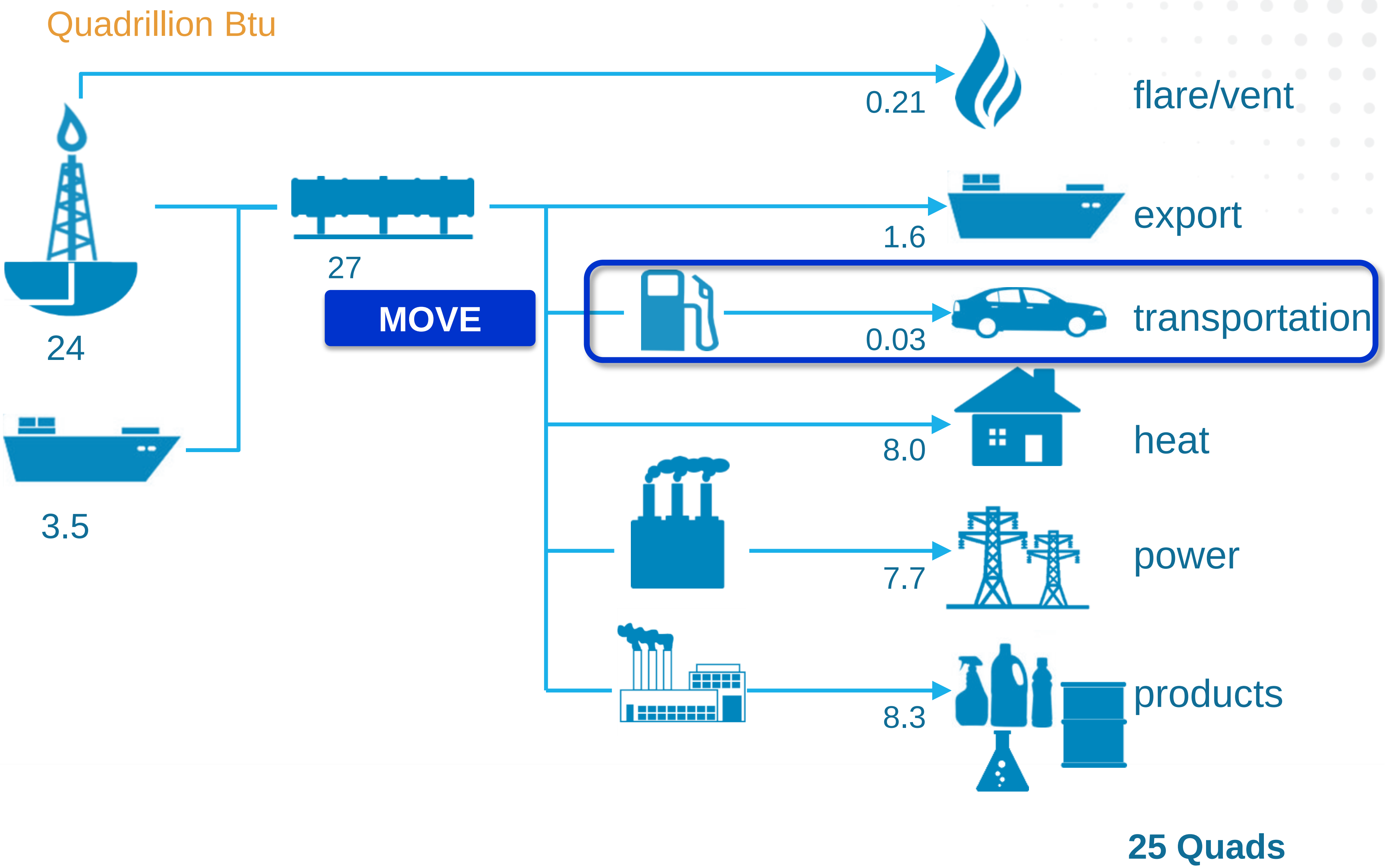






What else can we do with all our cheap natural gas?

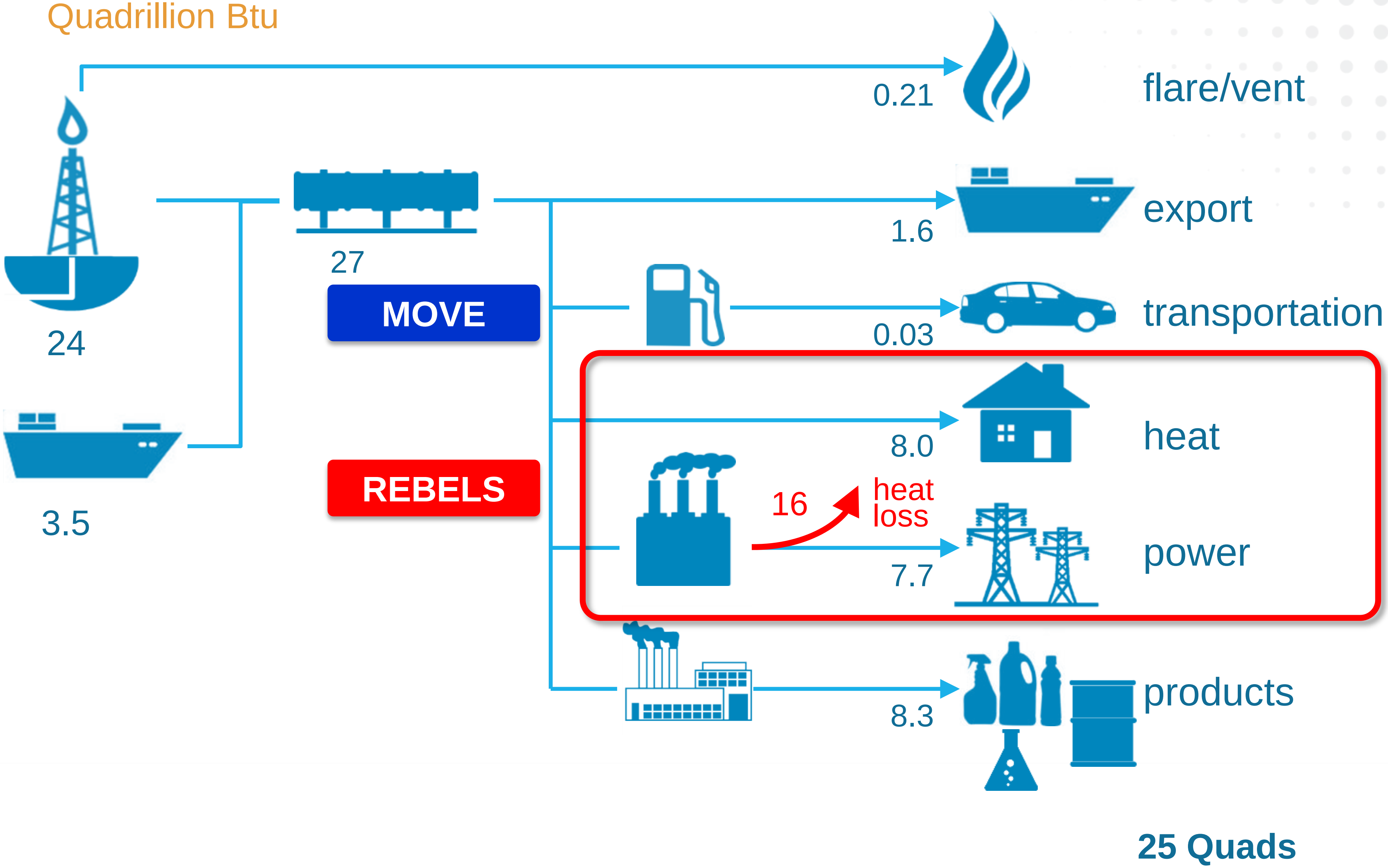
2011 U.S. Natural Gas Energy Flows



Source: U.S. Energy Information Agency, January, 2014, http://www.eia.gov/

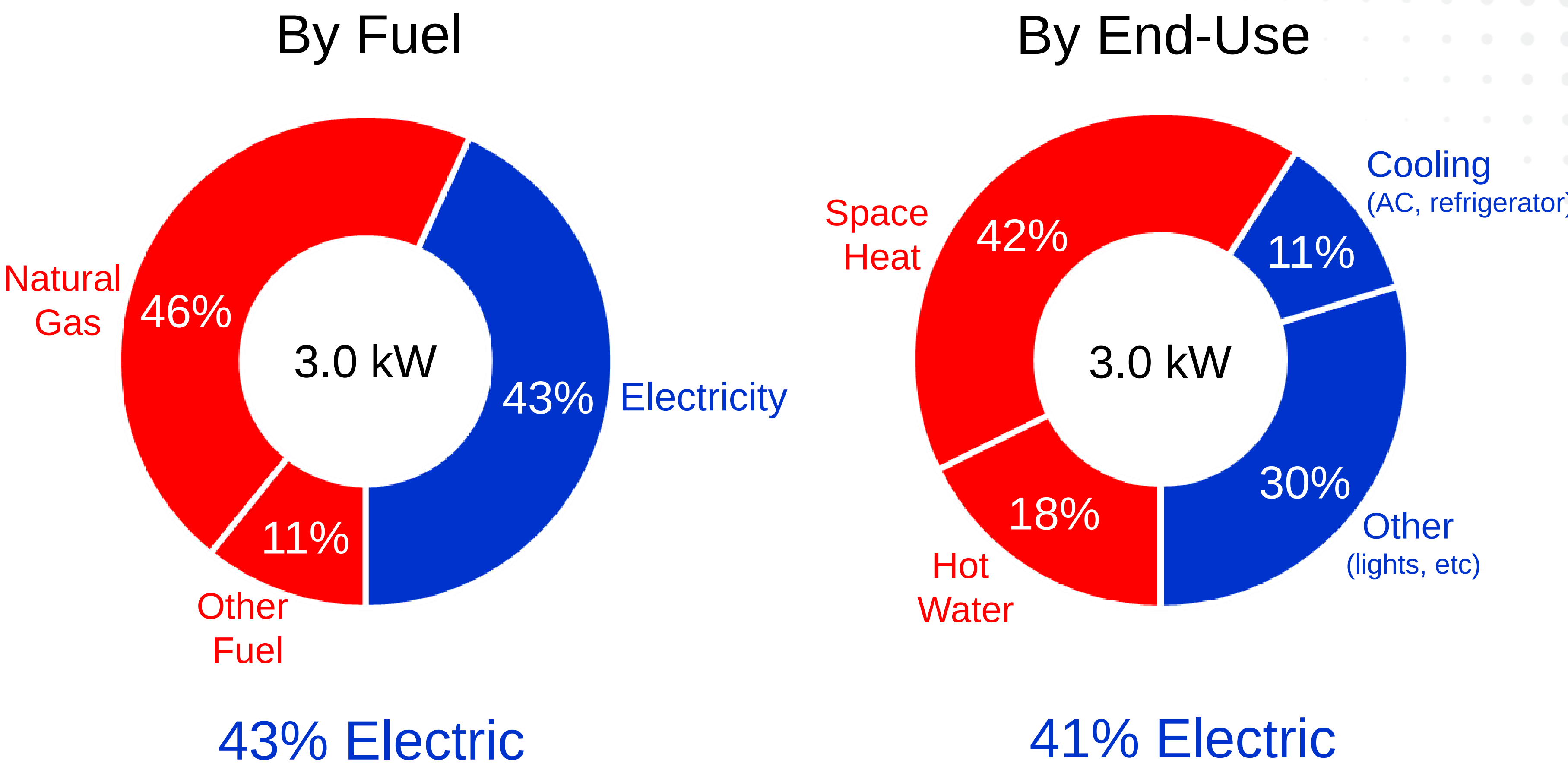
2011 U.S. Natural Gas Energy Flows

Quadrillion Btu



Source: U.S. Energy Information Agency, January, 2014, http://www.eia.gov/

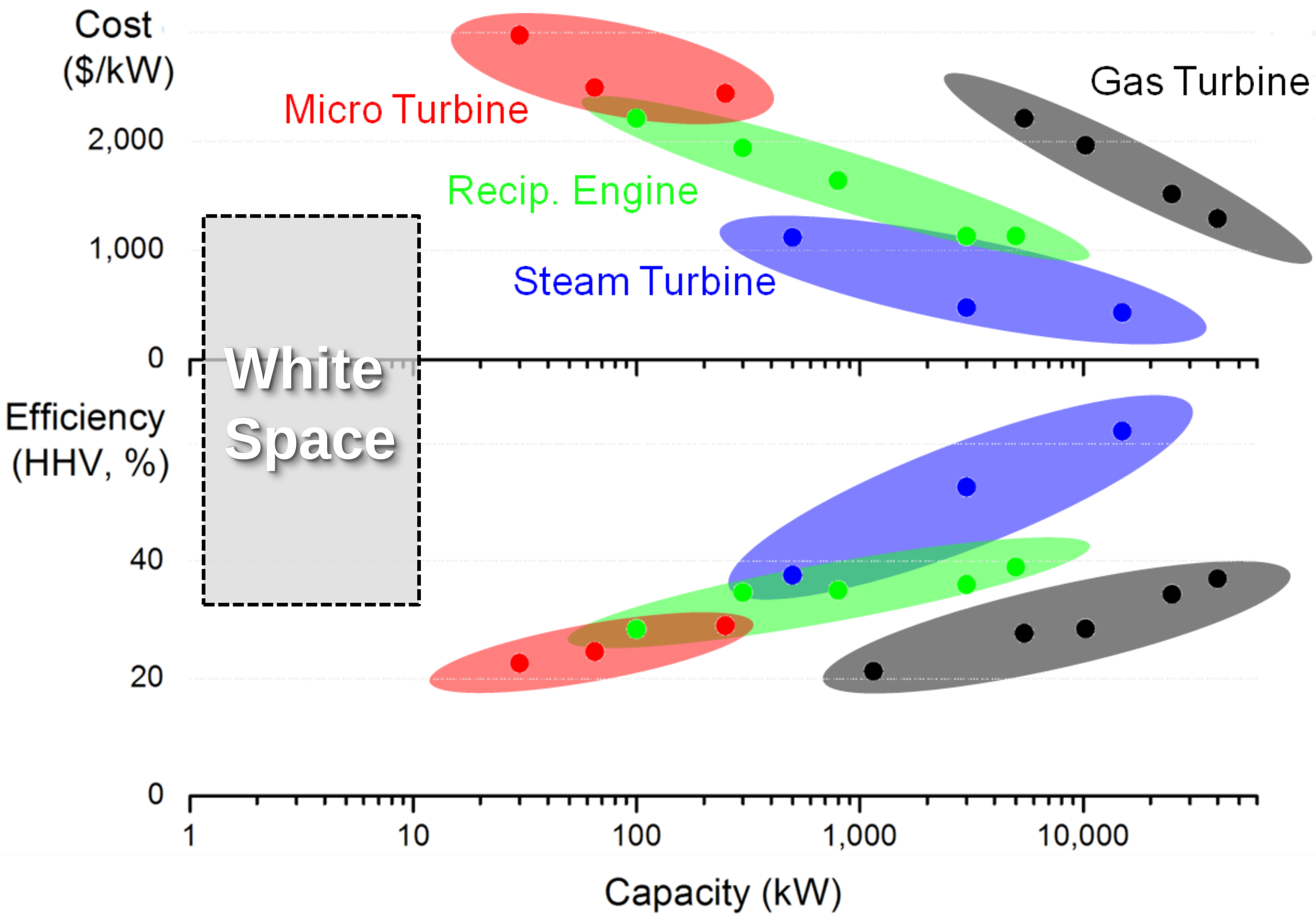
2009 U.S. Household Energy Use



Source: U.S. Energy Information Administration, Office of Energy Consumption and Efficiency Statistics, Forms EIA-457 A and C-G of the 2009 Residential Energy Consumption Survey.

The perfect home generator would have an electrical efficiency > 35%

Is there a small, cheap, efficient generator?



Source: Adapted from Catalog of CHP Technologies, U.S. Environmental Protection Agency Combined Heat and Power Partnership (2008).

Reliable Electricity Based on ELectrochemical Systems

Released: November 30, 2013

- Transformational electrochemical technologies to enable low-cost distributed power generation.
- Aims to enhance grid stability, increase energy security, and balance intermittent renewable technologies

Live FOA – “quiet period”

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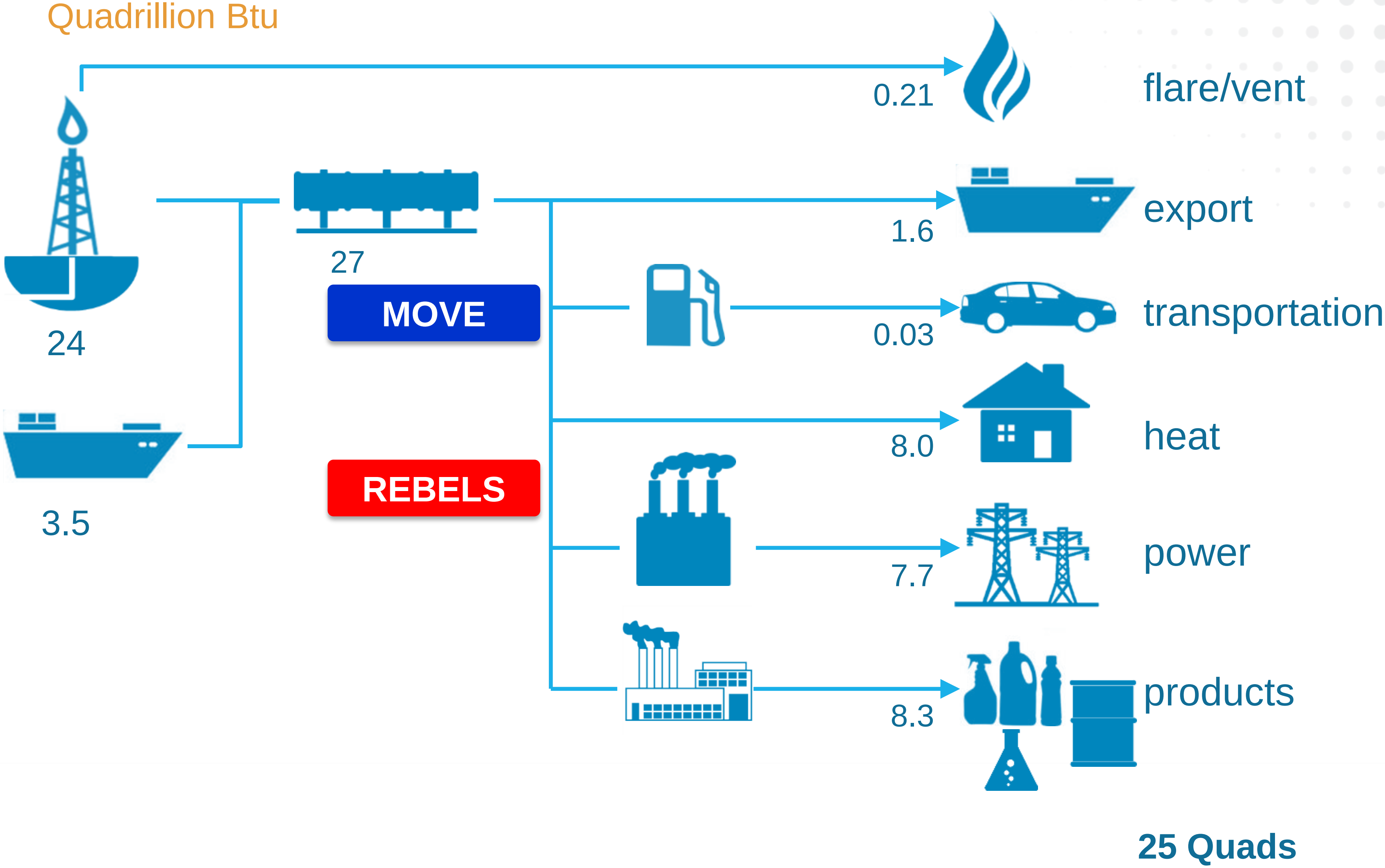
2011 U.S. Natural Gas Energy Flows

Quadrillion Btu



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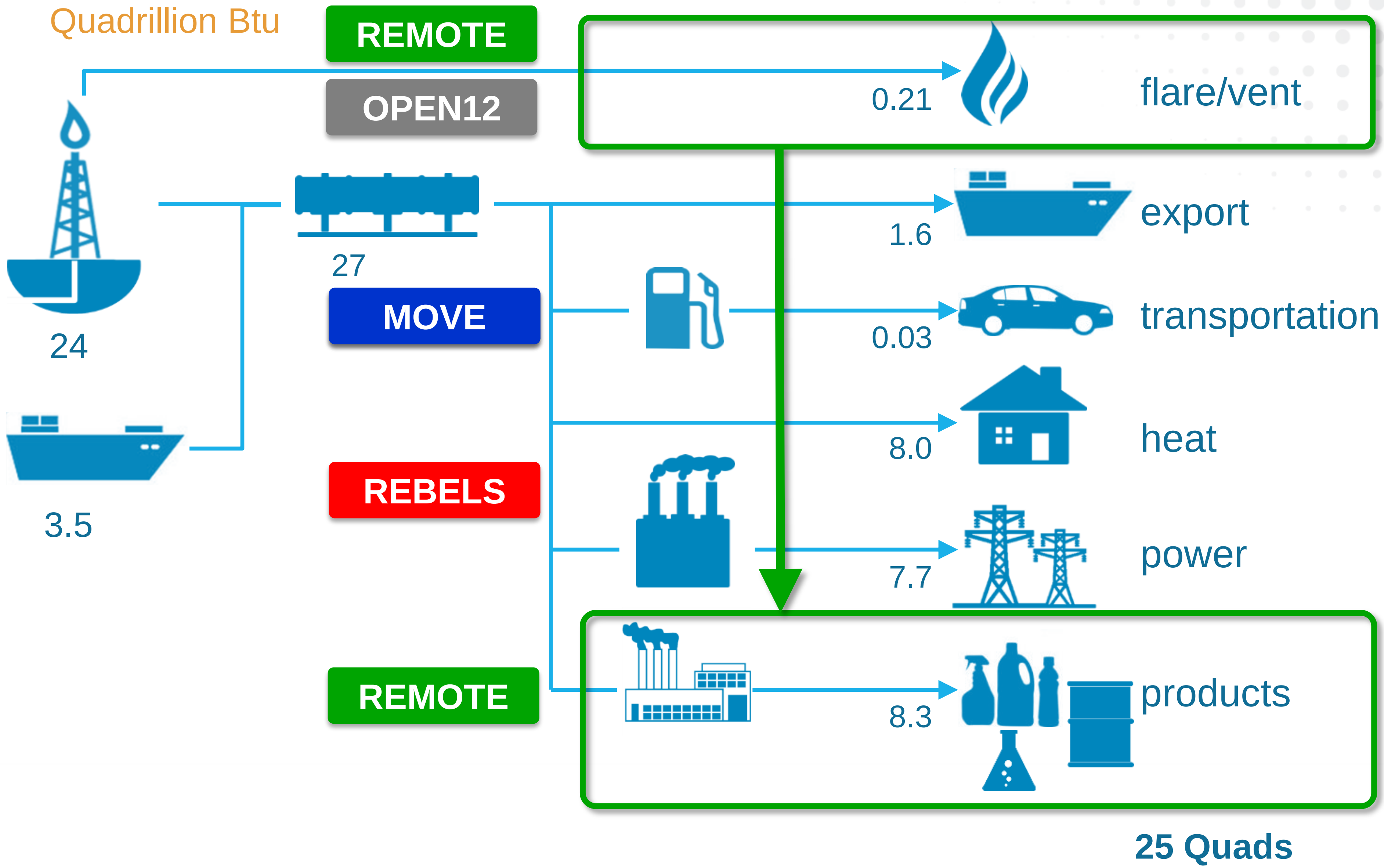
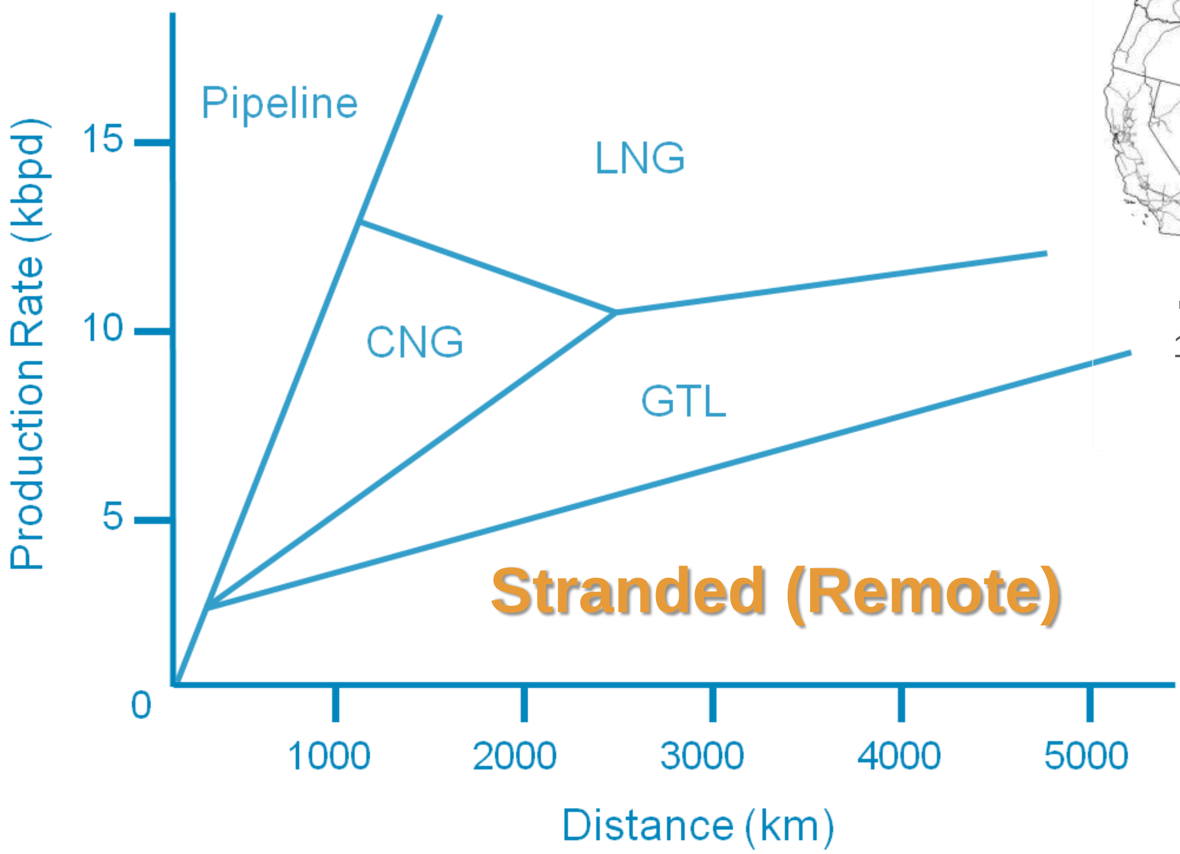
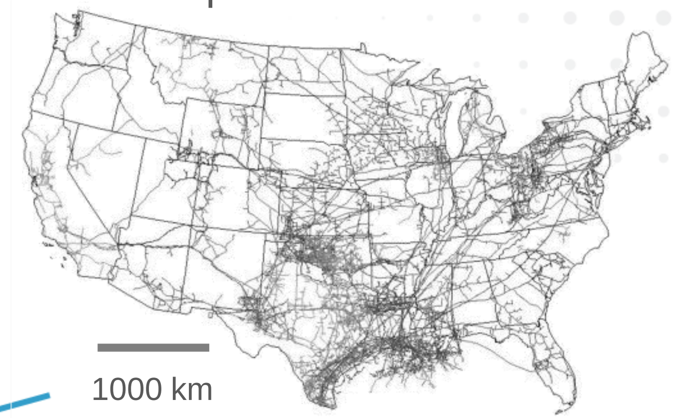


Source: U.S. Energy Information Agency, January, 2014, http://www.eia.gov/

Natural Gas Transport Economics



U.S. Natural Gas Pipeline Network



[1] kbpd = thousand barrels per day, oil equivalent) = 5.8 million Btu per day
[2] D Hawkins, TransOcean Global, Gas Flaring Reduction Conference, Paris Dec 13-15, 2006
[3] Energy Information Agency, Office of Oil & Gas, Natural Gas Division, Gas Transportation System, 2009

The problem is natural gas produced remotely can not be brought to market economically

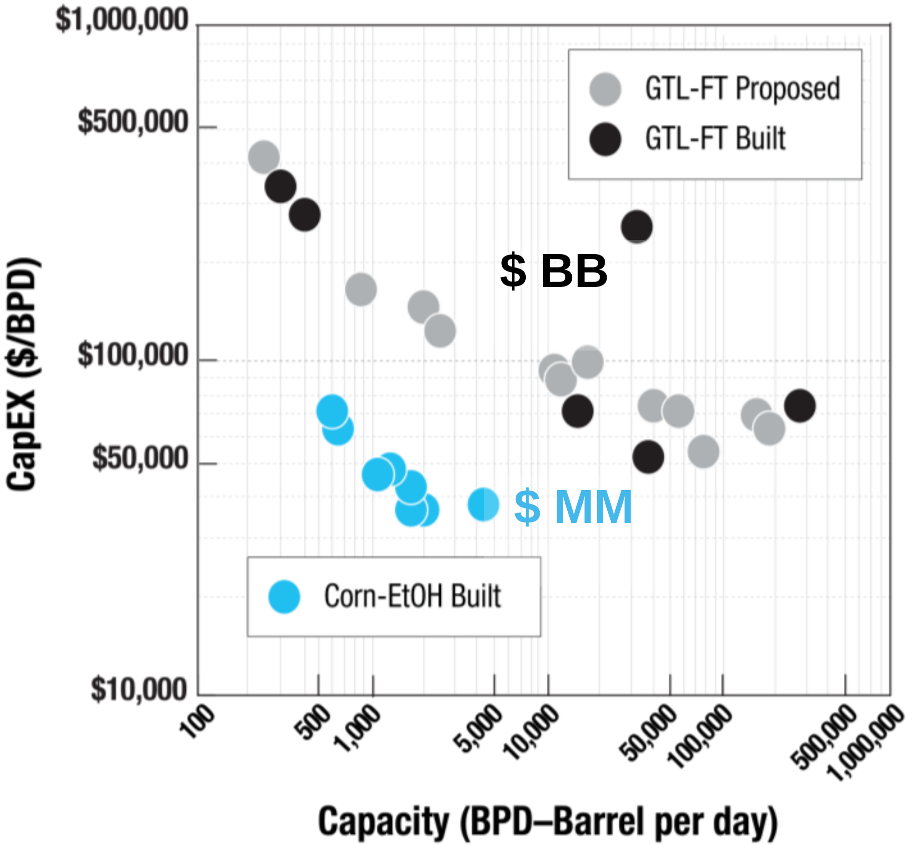
One solution is to convert it to liquids

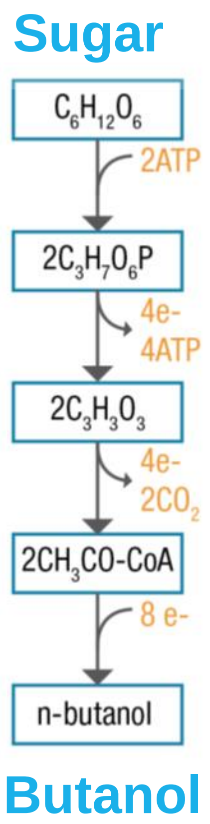
REMOTE Program

Reducing Emissions using Methanotrophic Organisms for Transportation Energy

Methane Bioconversion: White Space

Potentially low capital cost & high efficiency





97% $E_{eff.}$

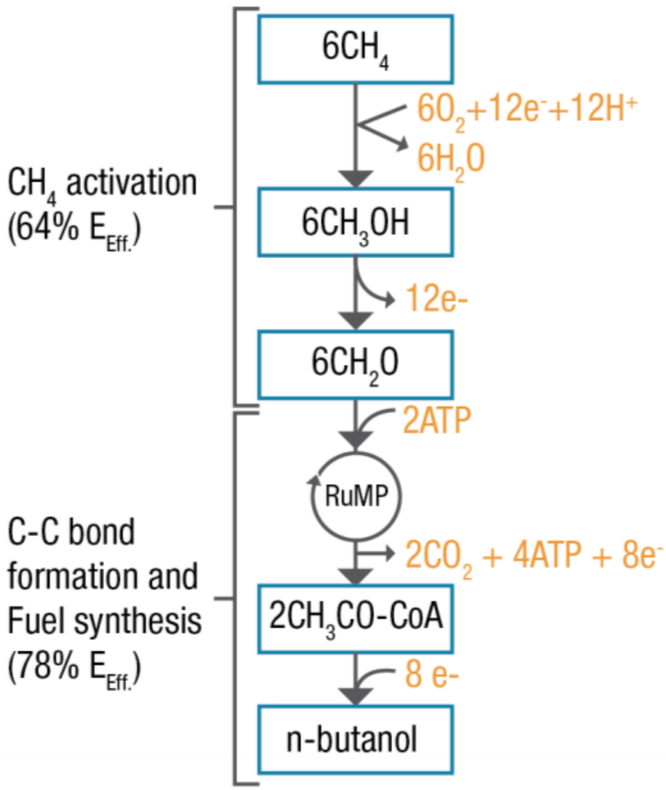
Conrado & Gonzalez, 2014. *Science,* 343: 621-623;
Gonzalez & Haynes, 2014. *Nat. Chem. Biol.* (MS in Review)

Methane Bioconversion Reconceptualized

n-butanol used as a proxy for liquid fuel/chemical

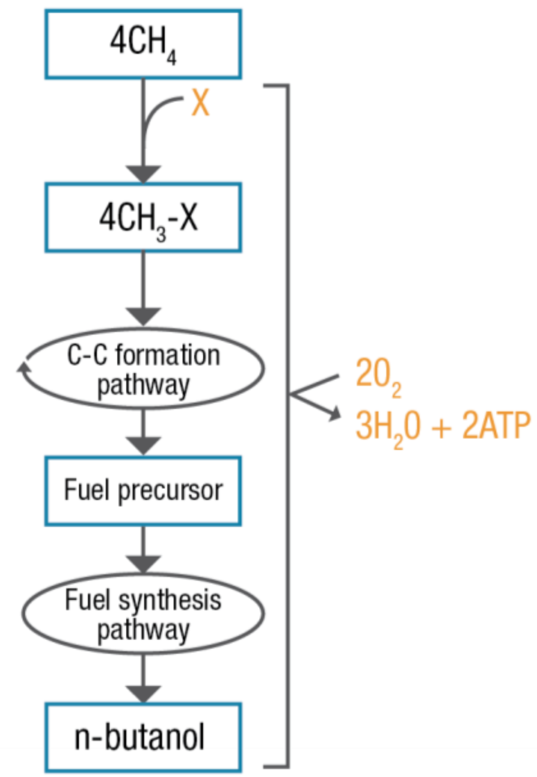
Current learning curve

51% E_{Eff} & 67% C_{Eff}



New concept

76% E_{Eff} & 100% C_{Eff}



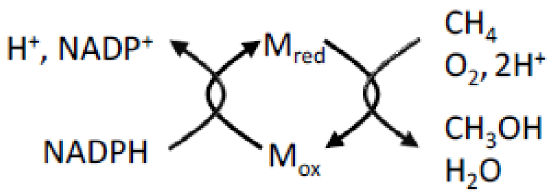
Conrado & Gonzalez, 2014. *Science,* 343: 621-623;
Gonzalez & Haynes, 2014. *Nat. Chem. Biol.* (MS in Review)

Hypothetical/Designed Solutions

Basis for techno-economic analysis (TEA)

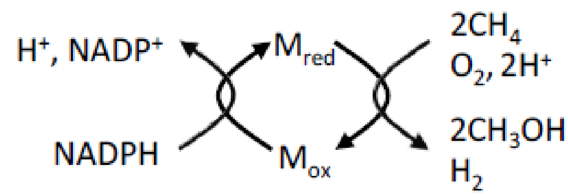
High Efficiency Methane Activation

Native methane monooxygenase: 61% $E_{Eff.}$



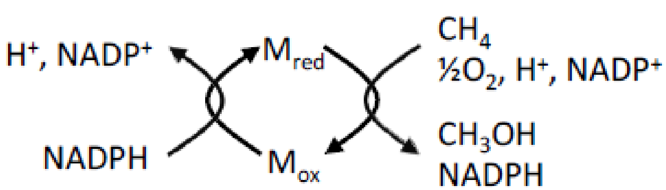
Net: $CH_4 + O_2 + NADPH + H^+ \rightarrow CH_3OH + H_2O + NADP^+$

Engineered methane dioxygenase: 80% $E_{Eff.}$



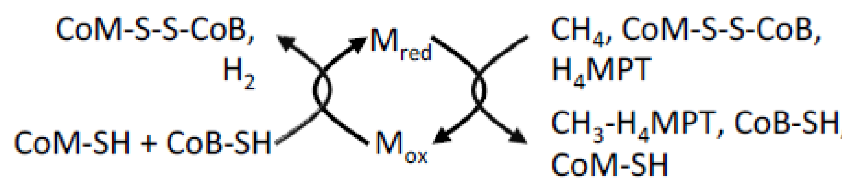
Net: $CH_4 + ½O_2 + ½NADPH + ½H^+ \rightarrow CH_3OH + ½H_2 + ½NADP^+$

Engineered MMO: 80% $E_{Eff.}$



Net: $CH_4 + ½O_2 \rightarrow CH_3OH$

Engineered methyl-coenzyme reductase: 80% $E_{Eff.}$



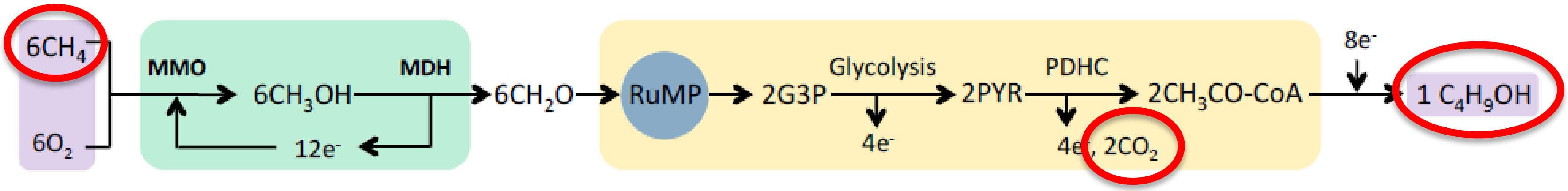
Net: $CH_4 + H_4MPT \rightarrow CH_3\text{-}H_4MPT + H_2$

arpa·e
CHANGING WHAT'S POSSIBLE

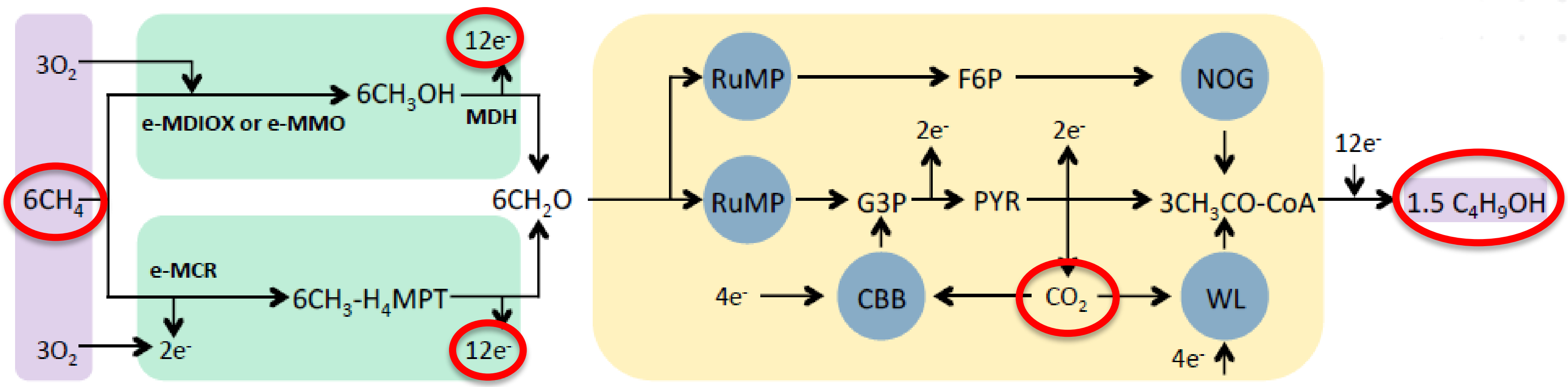
Conrado & Gonzalez, 2014. *Science*, 343: 621-623;
Gonzalez & Haynes, 2014. *Nat. Chem. Biol.* (MS in Review)

High Efficiency Fuel Synthesis

Current learning curve: 51% E_{Eff} & 67% C_{Eff}



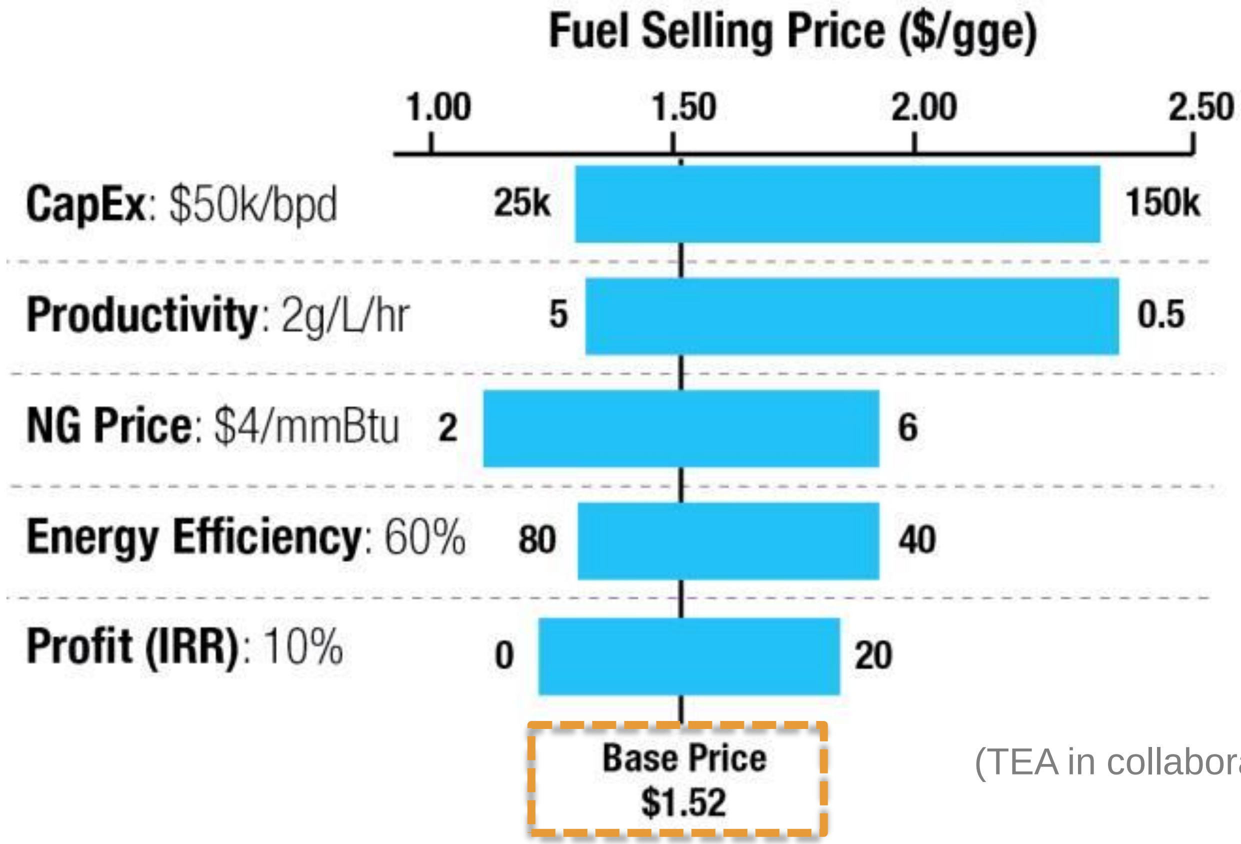
New concept: 76% E_{Eff} & 100% C_{Eff}



CHANGING WHAT'S POSSIBLE

Conrado & Gonzalez, 2014. *Science,* 343: 621-623;
Gonzalez & Haynes, 2014. *Nat. Chem. Biol.* (MS in Review)

Bioconversion: Cost-Competitive

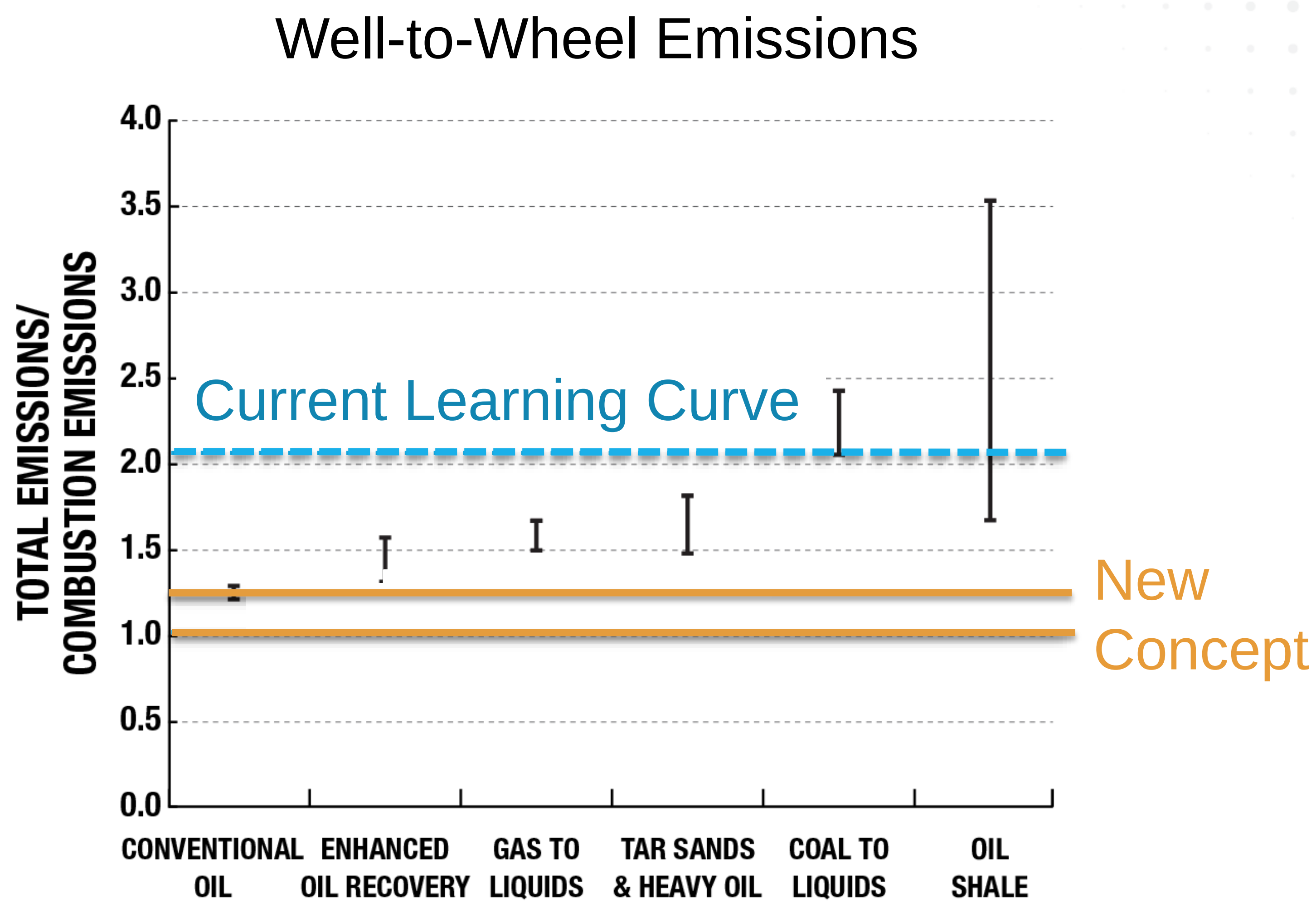


(TEA in collaboration with NREL)

Liquid fuel under $2.00/gge

Conrado & Gonzalez, 2014. *Science,* 343: 621-623;
Gonzalez & Haynes, 2014. *Nat. Chem. Biol.* (MS in Review)

Bioconversion: Small Carbon Footprint



Conrado & Gonzalez, 2014. *Science,* 343: 621-623;
Gonzalez & Haynes, 2014. *Nat. Chem. Biol.* (MS in Review)

REMOTE Portfolio (15 projects, $34M)

DE-FOA-0000672, CFDA No. 81.135

CAT 1: High-efficiency biological activation of methane

Anaerobic MICHIGAN

Aerobic BERKELEY LAB

Arzeda.

NORTHWESTERN UNIVERSITY

CAT 1&2:

MIT

PENNSTATE 1855

UD

MOgene

CAT 2: High-efficiency biological synthesis of fuel

UCLA

coskata

UCDAVIS

UNIVERSITY of WASHINGTON

CAT 3: Process intensification for biological CH_4 conversion

OSU Oregon State UNIVERSITY

CALYSTA Energy™

LanzaTech

greenlight BIOSCIENCES

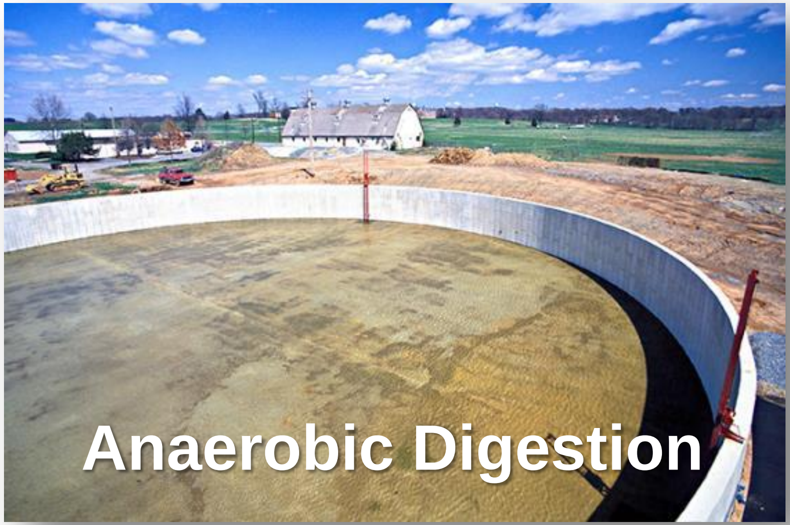
*Includes 1 OPEN 2012 project and 15 REMOTE projects

Is natural gas just a “bridge” to renewables or is it the renewable fuel of the future?

(Bio)methane as a "renewable" option?

High TRL, Low Impact

- Today methanogenic organisms generate methane during organic decomposition
- Deployed largely for emissions control



Low efficiency, low productivity

(Bio)methane as a "renewable" option?

Low TRL, High Impact

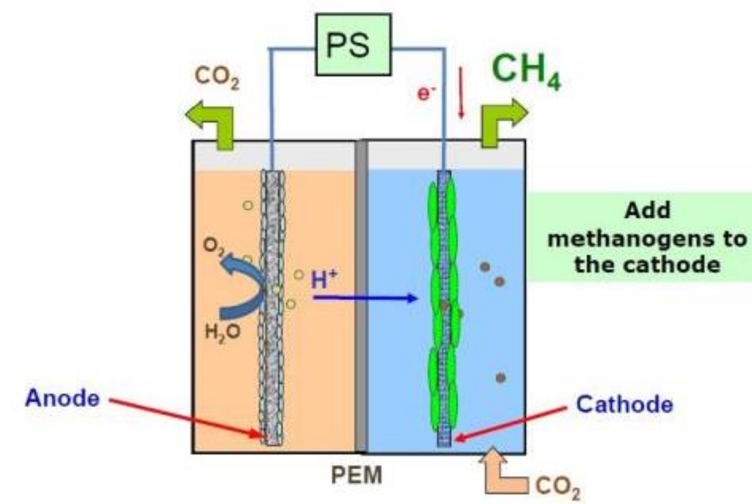
- Methanogens could generate CH_4 from CO_2 reduced by renewable hydrogen or electrons
- $CO_2 + 8e^- + 8H^+ \rightarrow CH_4 + 2H_2O$

Direct Biological Conversion of Electrical Current into Methane by Electromethanogenesis

SHAOAN CHENG, DEFENG XING, DOUGLAS F. CALL, AND BRUCE E. LOGAN*

Engineering Environmental Institute and Department of Civil and Environmental Engineering, 212 Sackett Building, The Pennsylvania State University, University Park, Pennsylvania 16802

Received December 12, 2008. Revised manuscript received March 5, 2009. Accepted March 6, 2009.

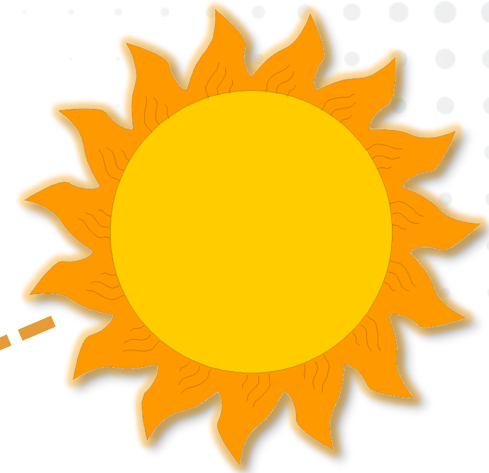


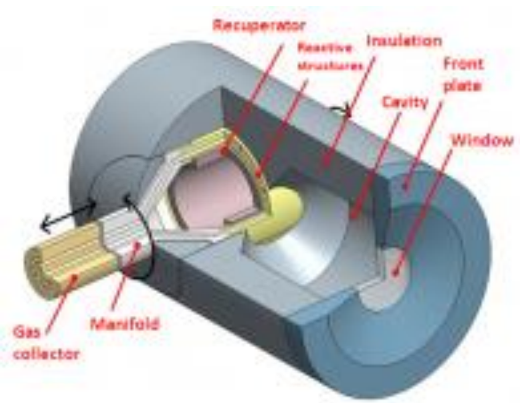
High efficiency, high risk

Cheng, Xing, Call, Logan. *Environ. Sci. Technol.* (2009) **43**, 3953-3958

(Solar)methane as a “renewable” option?

- Convert carbon dioxide and water to methane using solar heat
- Many options for solar thermochemical cycles





Example

$$CeO_2 + \text{heat} = CeO_{2-\delta} + O_2$$

$$CO_2 + H_2O + CeO_{2-\delta} = CH_4 + CeO_2$$

$$CO_2 + H_2O + \text{heat} = CH_4 + O_2$$

HEATS Program | University of Minnesota | UF University of Florida

Natural Gas Session

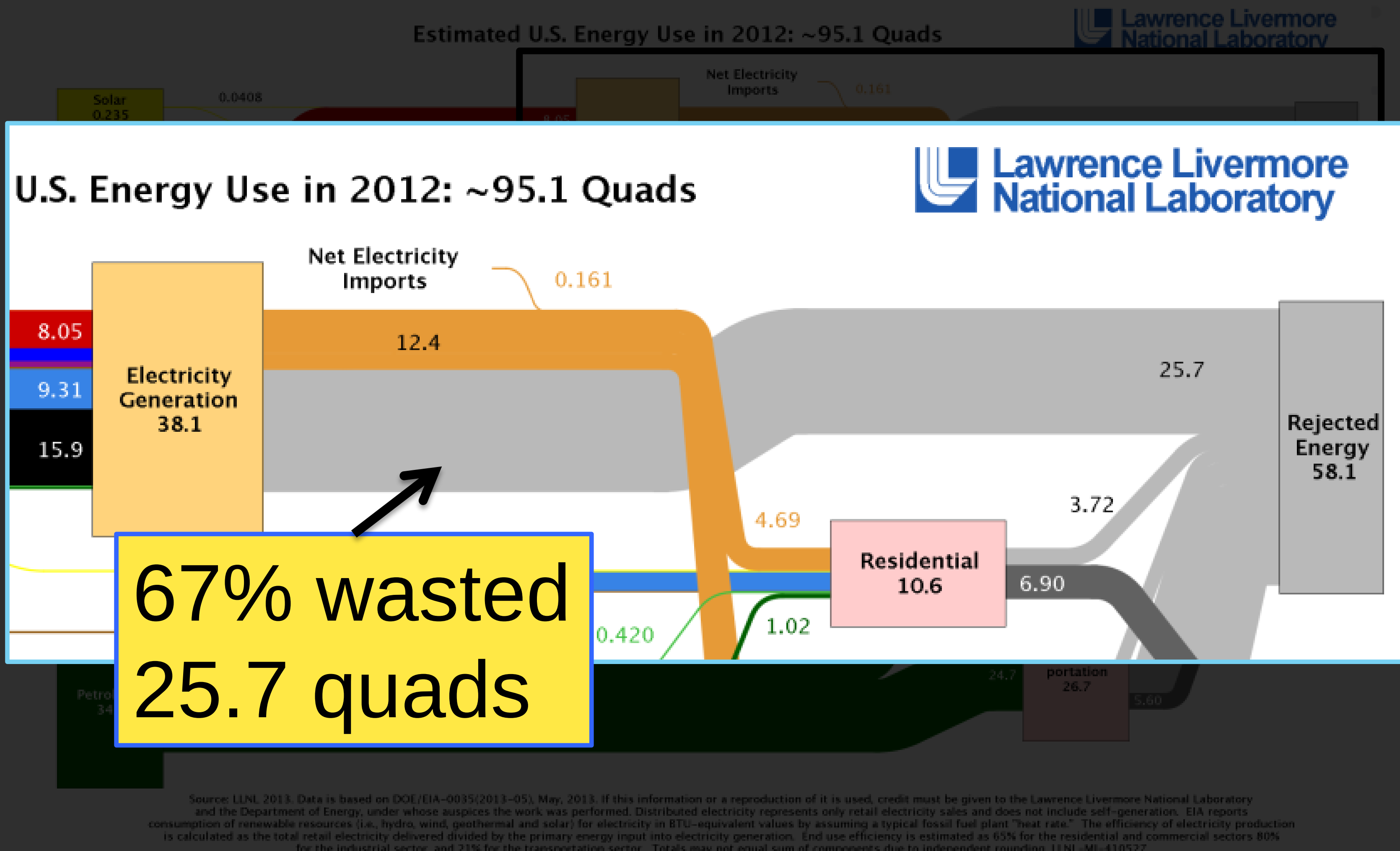
I. Background
- history, current status — Bryan Willson

II. Risks & Challenges
- environmental, economic — Bryan Willson

III. Opportunities
- transportation, heat & power — Dane Boysen
- conversion, renewable gas — Ramon Gonzalez
- new areas, emerging ideas — Ashwin Salvi

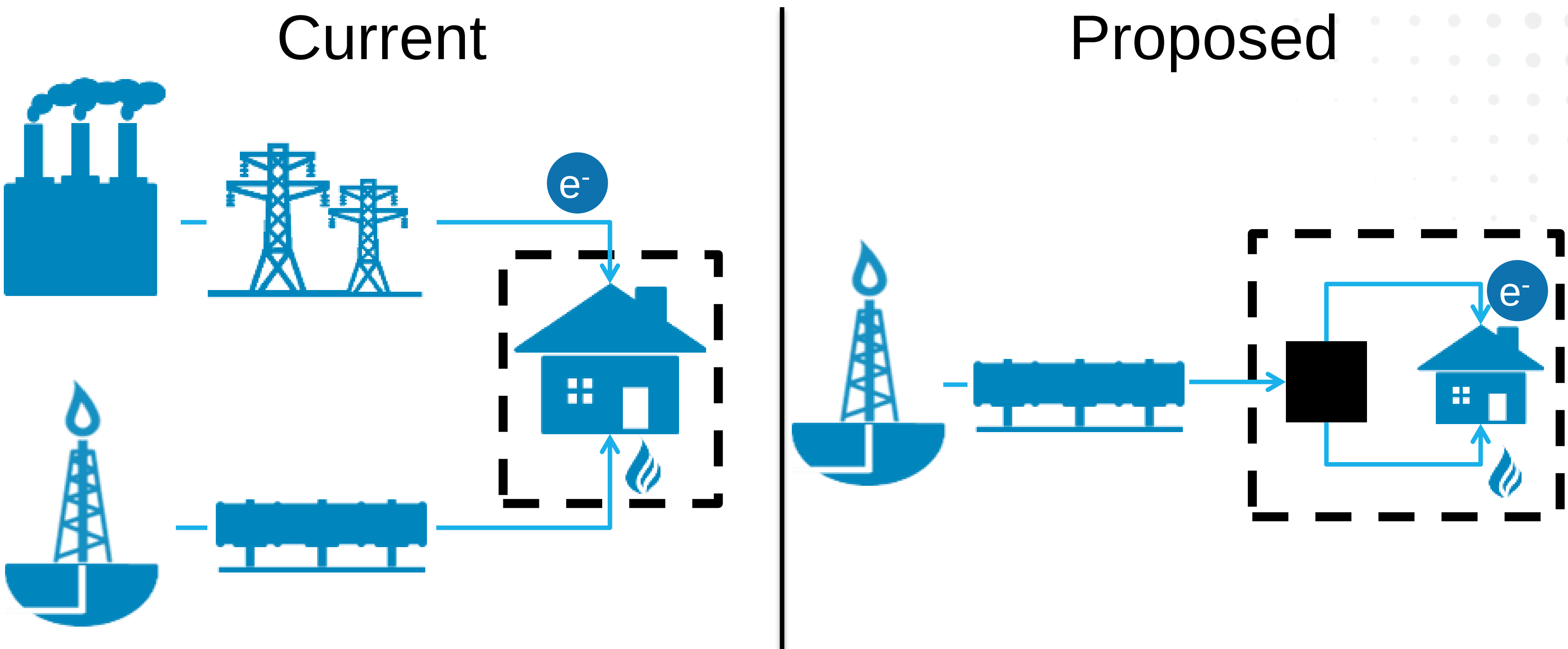
What's next
Distributed Cogeneration?

Centralized power waste



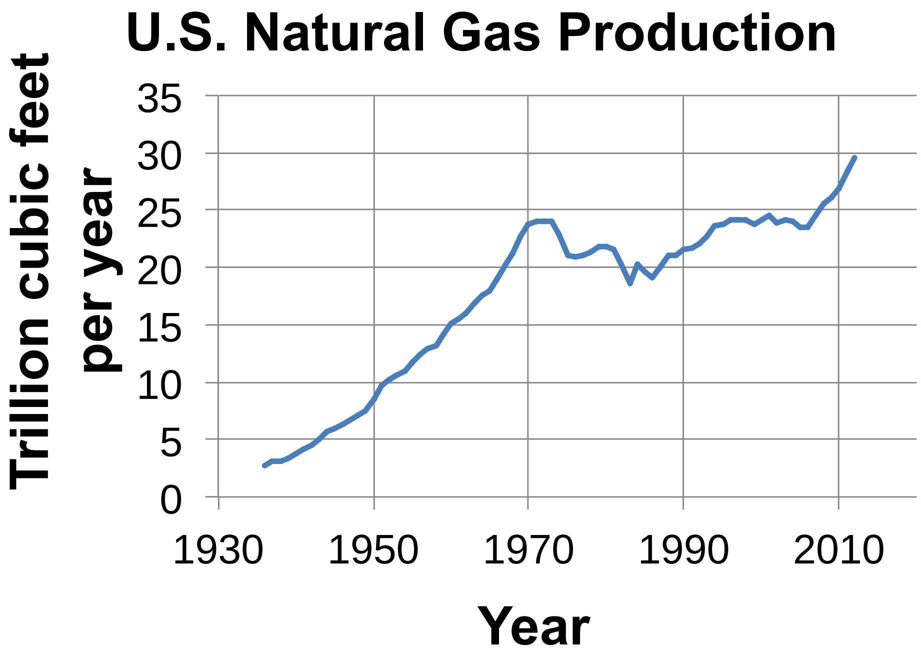
67% wasted
25.7 quads

Micro distributed generation



$\$ = e^- + NG + CAPEX$ > $\$ = NG + CAPEX$

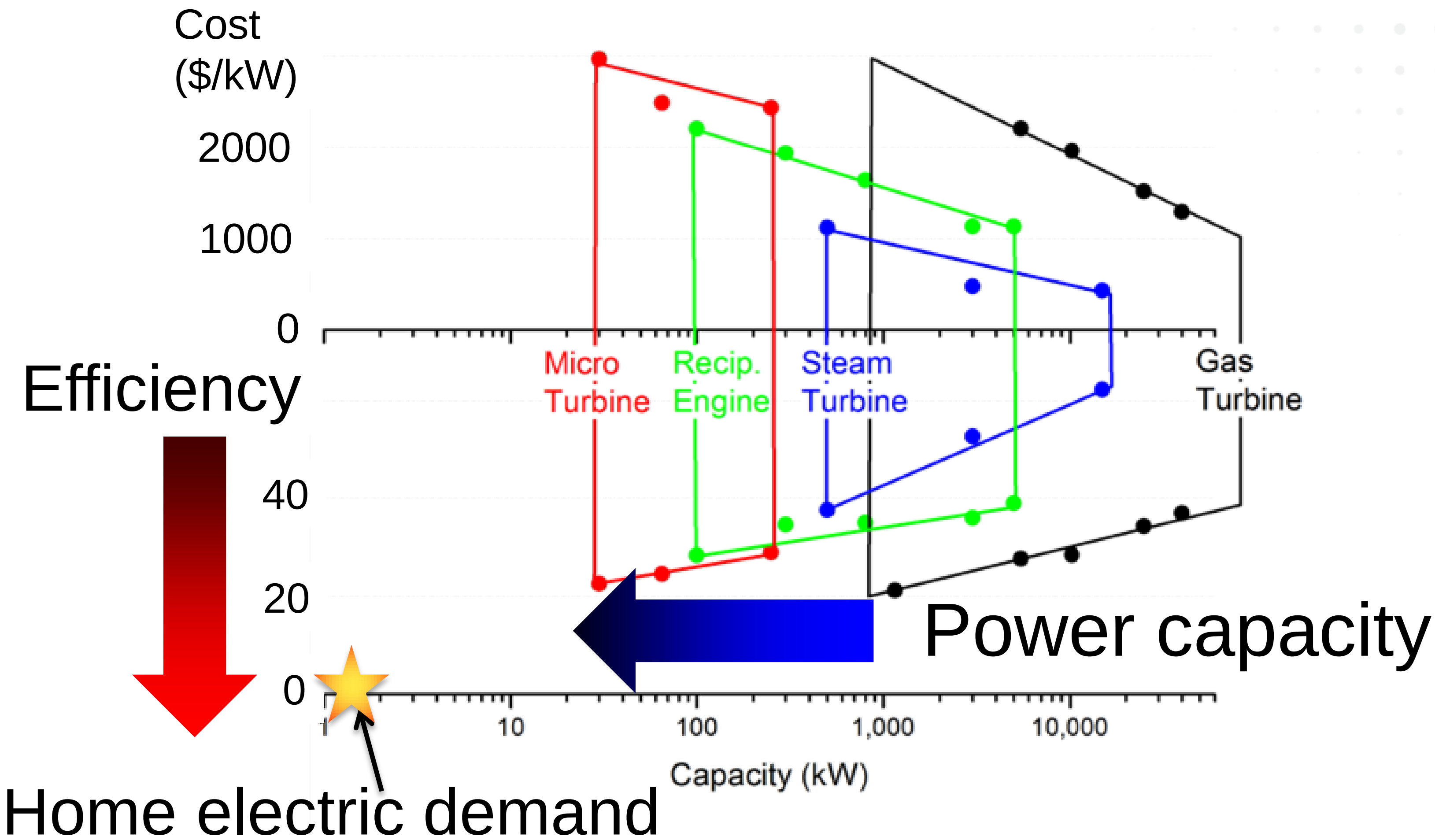
Natural gas - abundant and cheap



$0.036/kWh

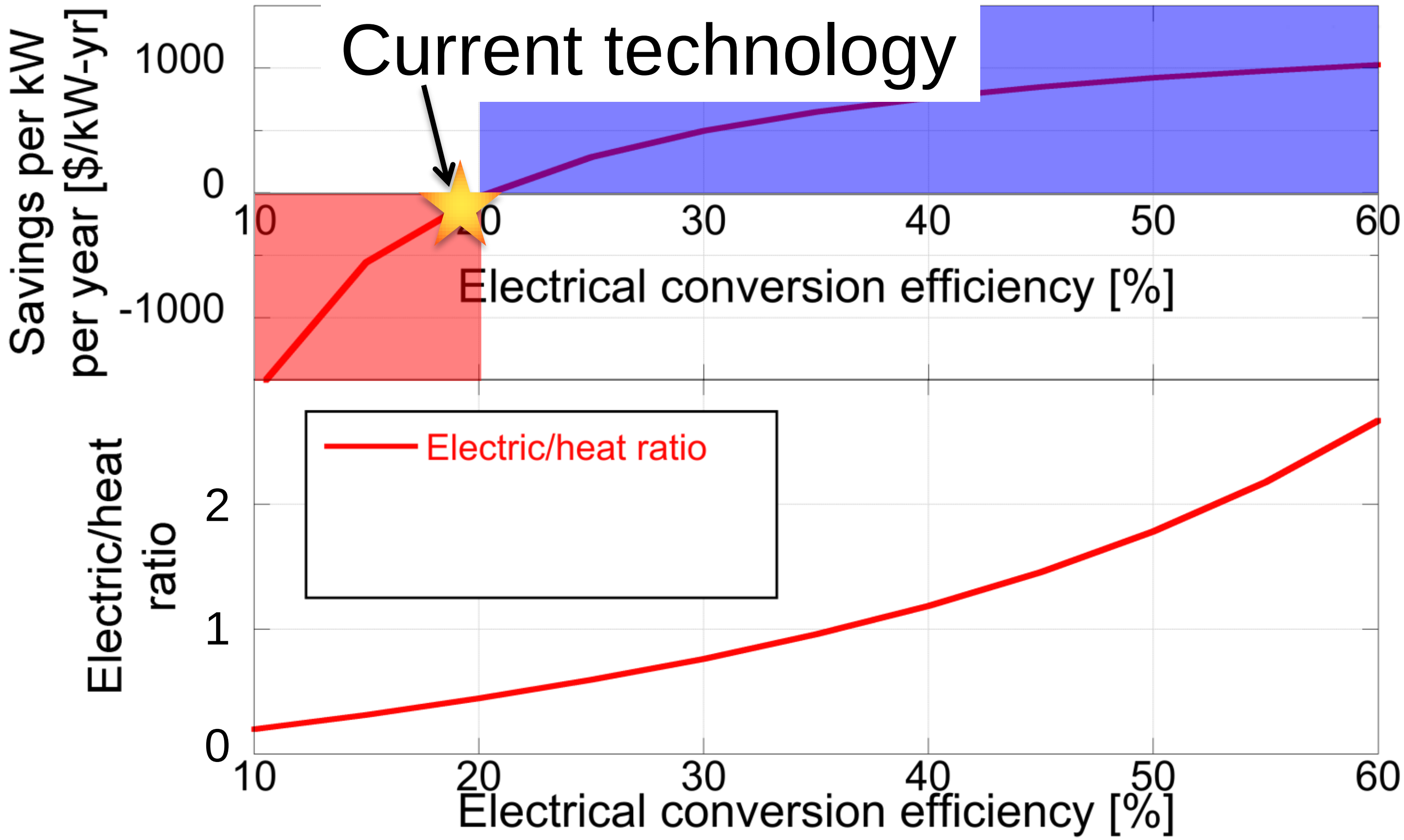
…So what's the problem?

Lower power, lower efficiency



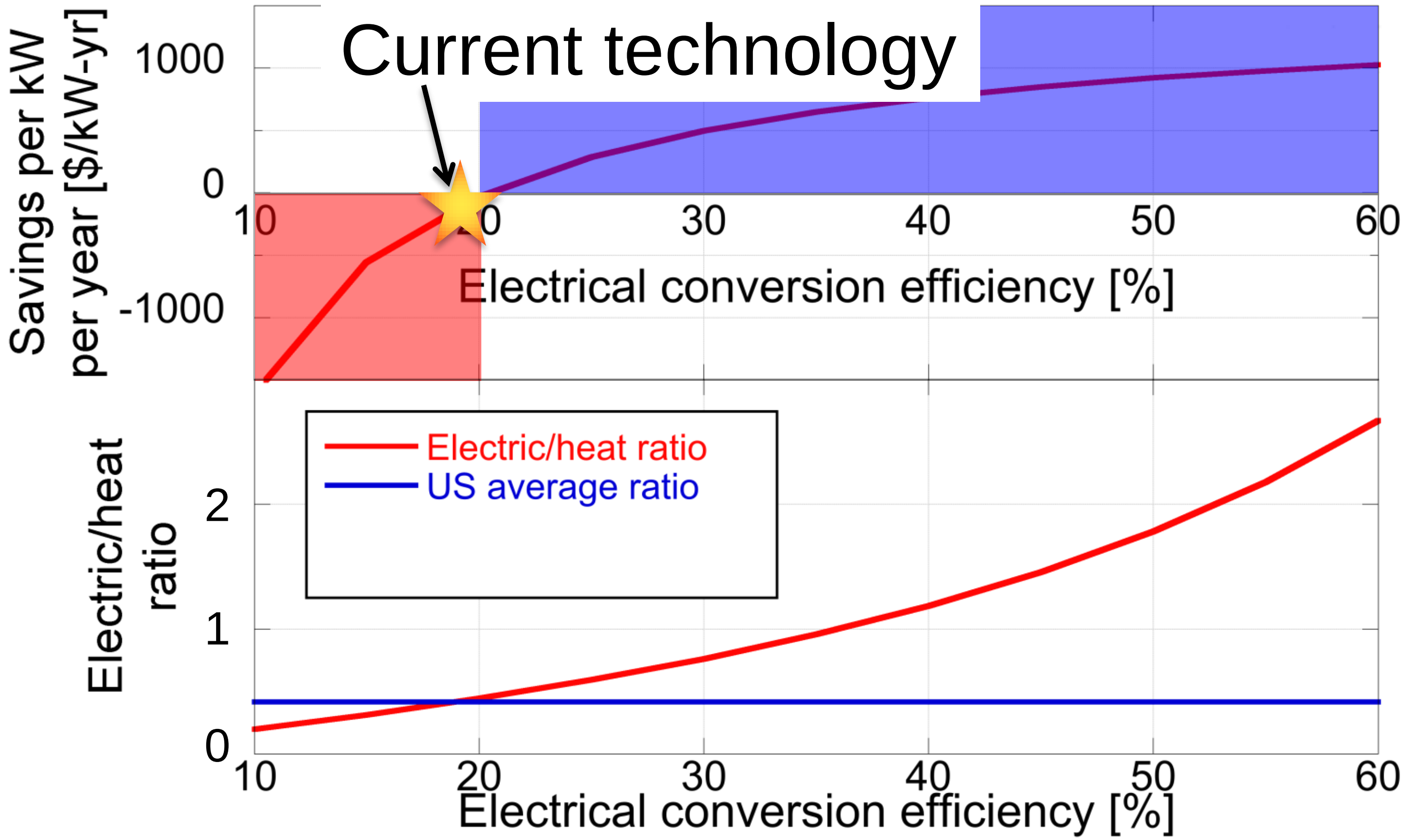
Variable consumer savings and demand

Distributed generation



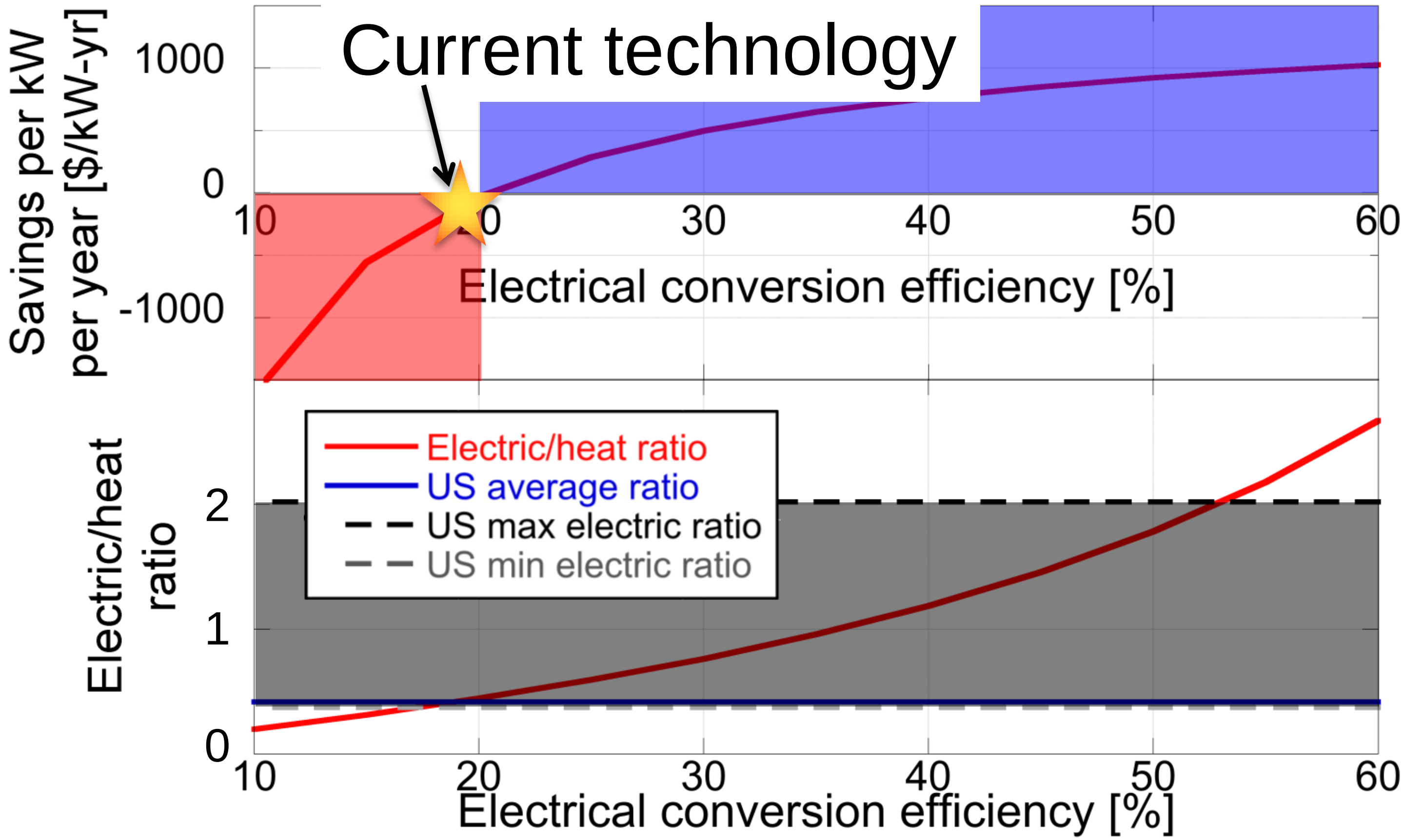
Variable consumer savings and demand

Distributed generation

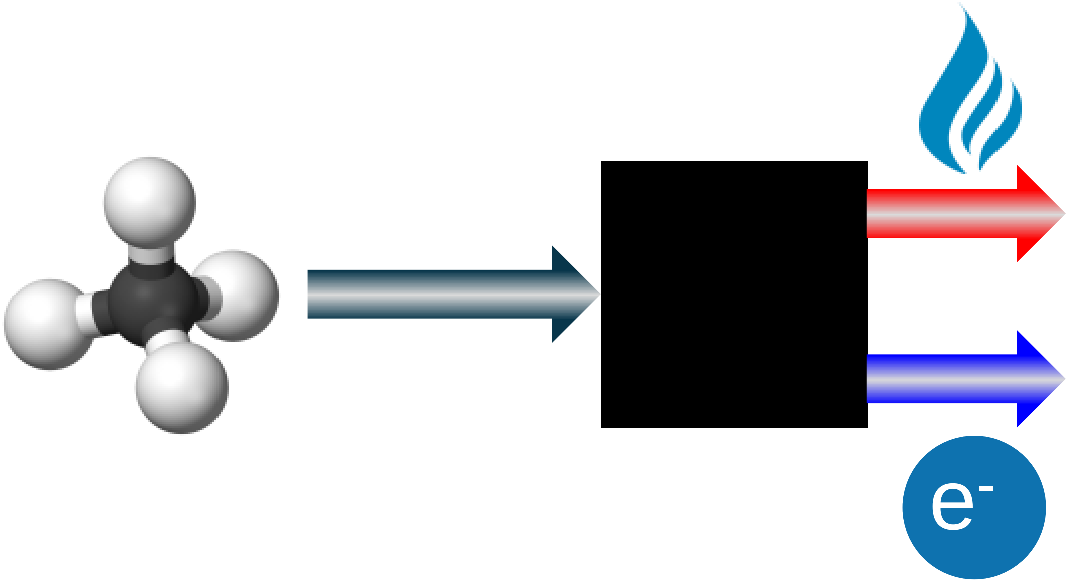


Variable consumer savings and demand

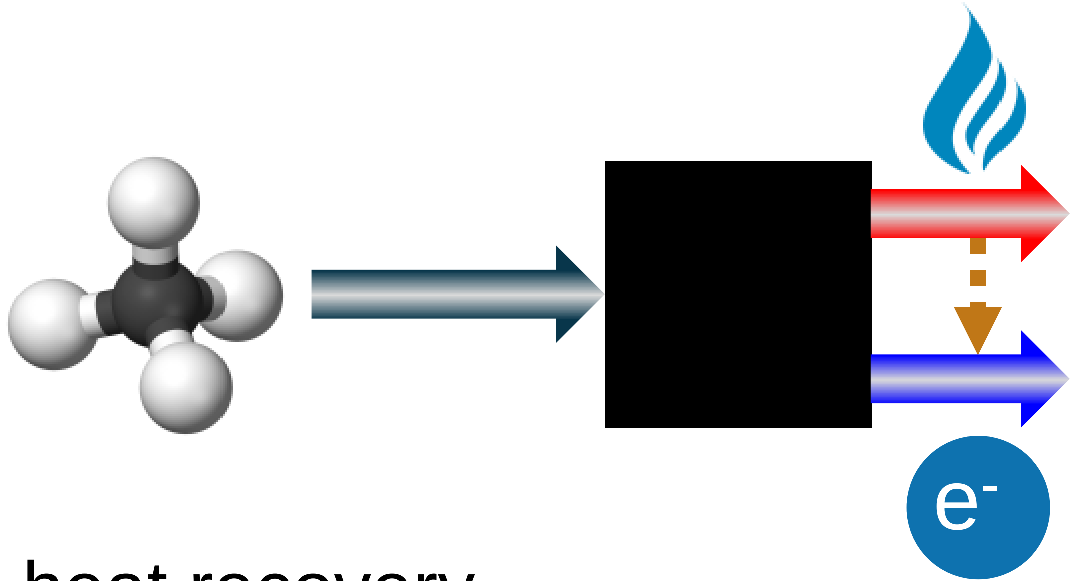
Distributed generation



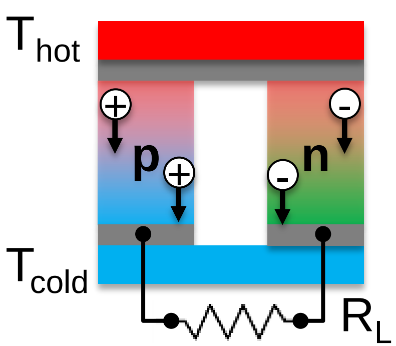
Potential approaches for electrical efficiency



Potential approaches for electrical efficiency

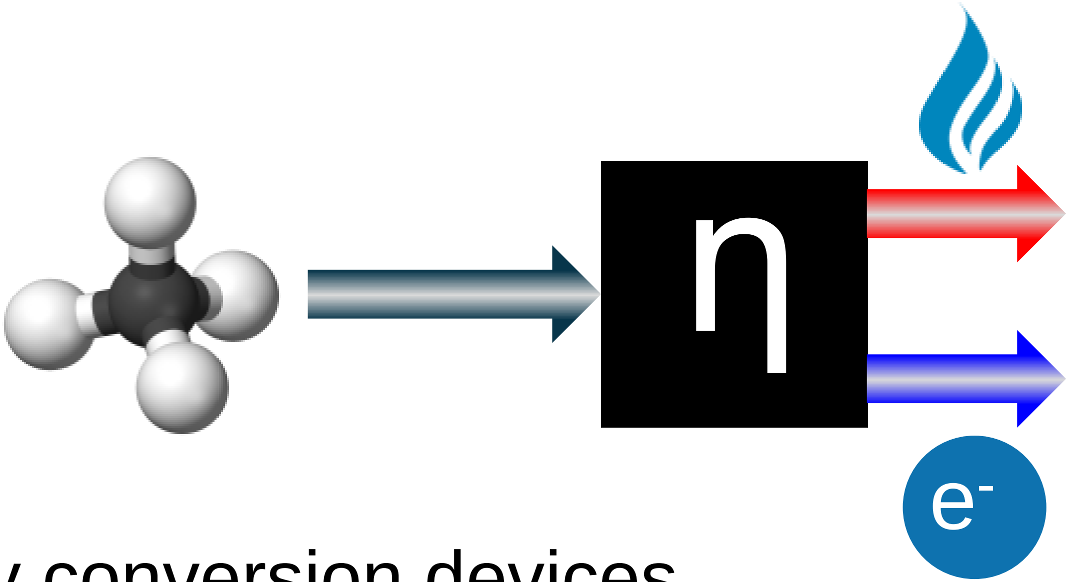


Waste heat recovery



CHANGING WHAT'S POSSIBLE

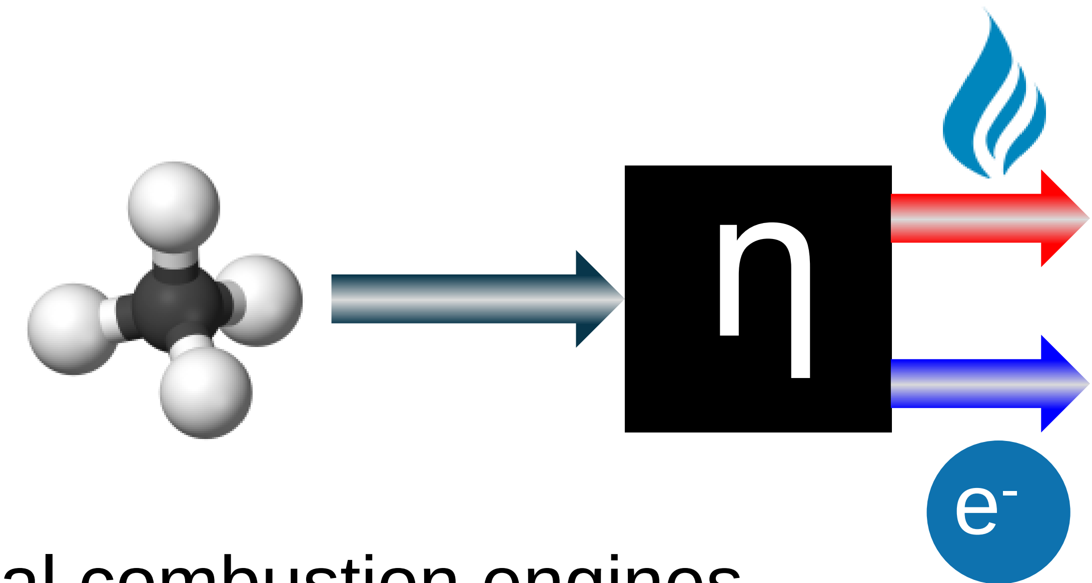
Potential approaches for electrical efficiency



Energy conversion devices

- Gas turbines, Steam turbines, Stirling engines, Internal combustion engines, Fuel cells

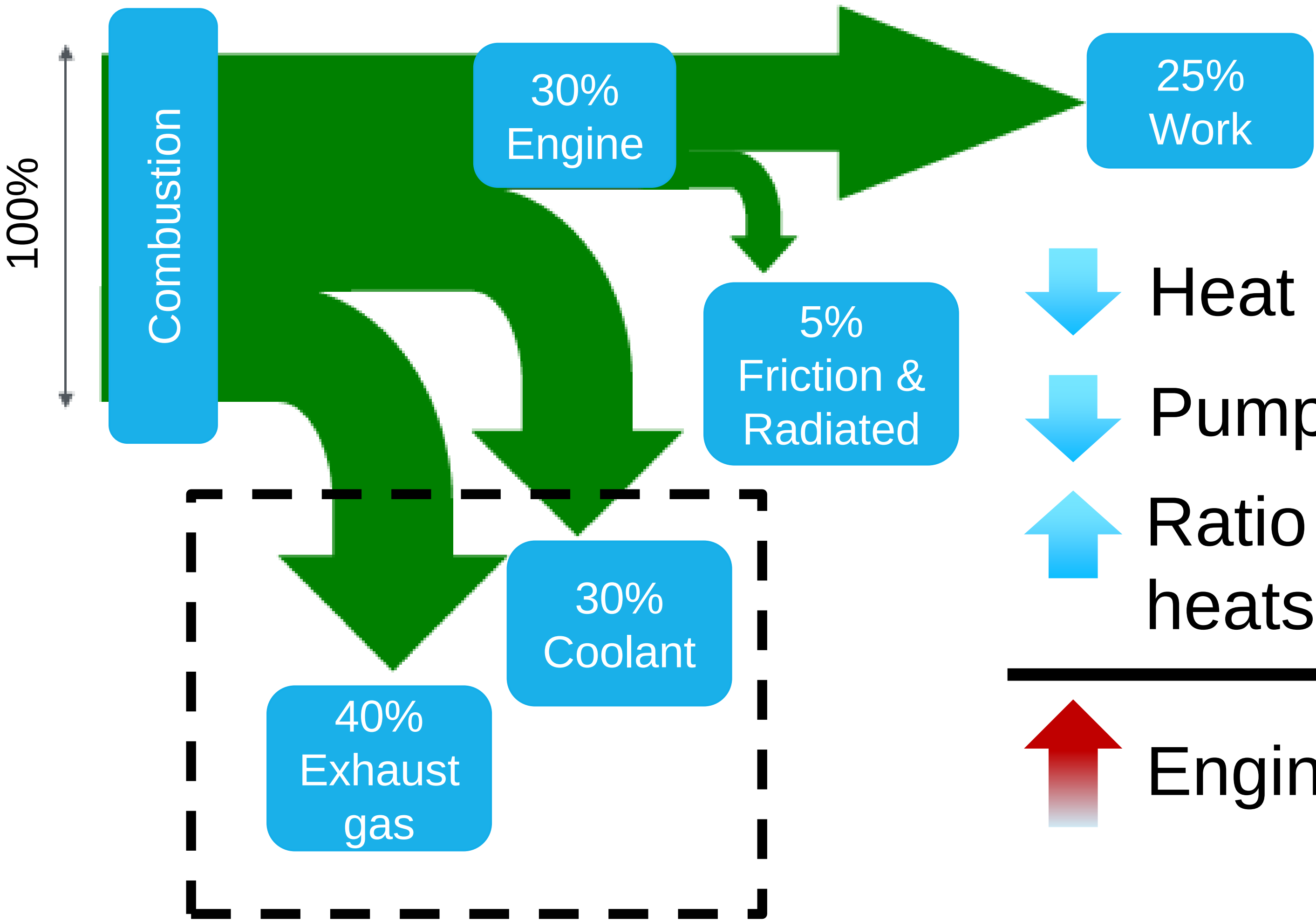
Potential approaches for electrical efficiency



Internal combustion engines




Typical engine losses



- ↓ Heat loss
- ↓ Pumping losses
- ↑ Ratio of specific heats

↑ Engine efficiency

Fairbanks, J. Directions in Engine-Efficiency and Emissions Research 2011

All sparks but no fire

A need for better ignition systems

New York Times, April 13, 2013.

Summary

Distributed generation efficiency and flexibility is key

At 30% electrical conversion efficiency, µDG system saves 7.5 Quads of primary energy

Dr. Ji-Cheng Zhao

Interests

- Heat Engines, Turbines, Materials, Natural Gas, High Temperature Materials, Energy Conversion and Storage Devices

Background

- Professor of Materials Science and Engineering, The Ohio State University (2007-2013)
- Senior Materials Scientist, GE Global Research (1995-2007)
- Hull Awardee, GE Global Research (2001)

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