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U.S. DEPARTMENT OF ENERGY

U.S. Industrial Sector Energy Use and Decarbonization Analysis

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Session 4. Electrification of the Industry Sector

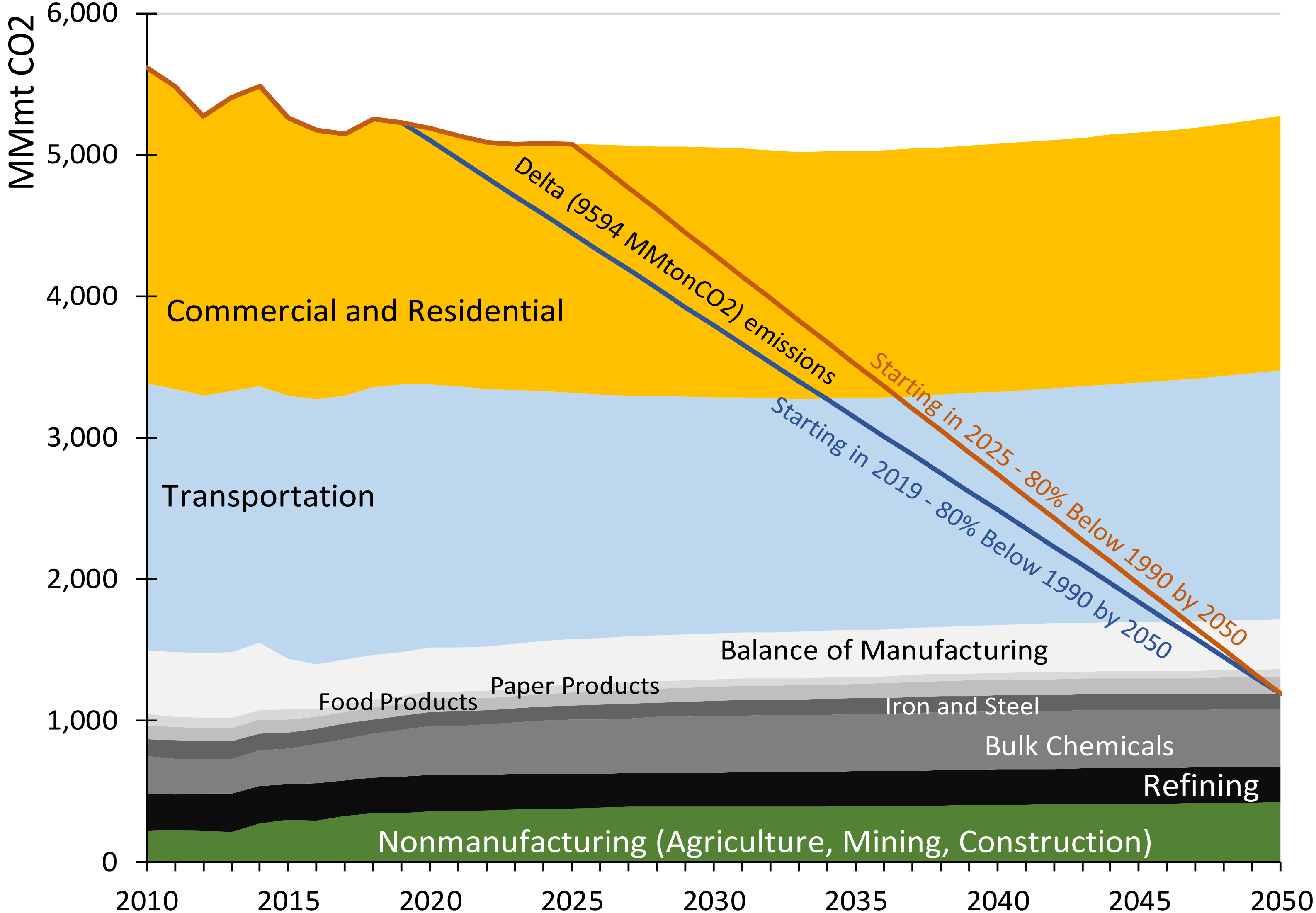
Technologies and Policies to Decarbonize the Industry Sector

Aspen, CO
November 12-16, 2018

What I had planned to talk about

1. End-use energy consumption sub-sector level (e.g., iron and steel, refining, chemicals, etc.)
2. A Comparisons of Fuel versus Electric Costs
3. U.S. Manufacturing Value Add, Gross Surplus, and Energy Costs
4. Techno-Econ Analysis of Energy Efficiency and Carbon Capture at U.S. Refineries - Example of the economics of decarbonizing the U.S. refinery sector.

U.S. CO2 Emission: AEO 2018 RC



EIA Annual Energy Outlook 2018 Reference Case (http://www.eia.gov/forecasts/aeo/)

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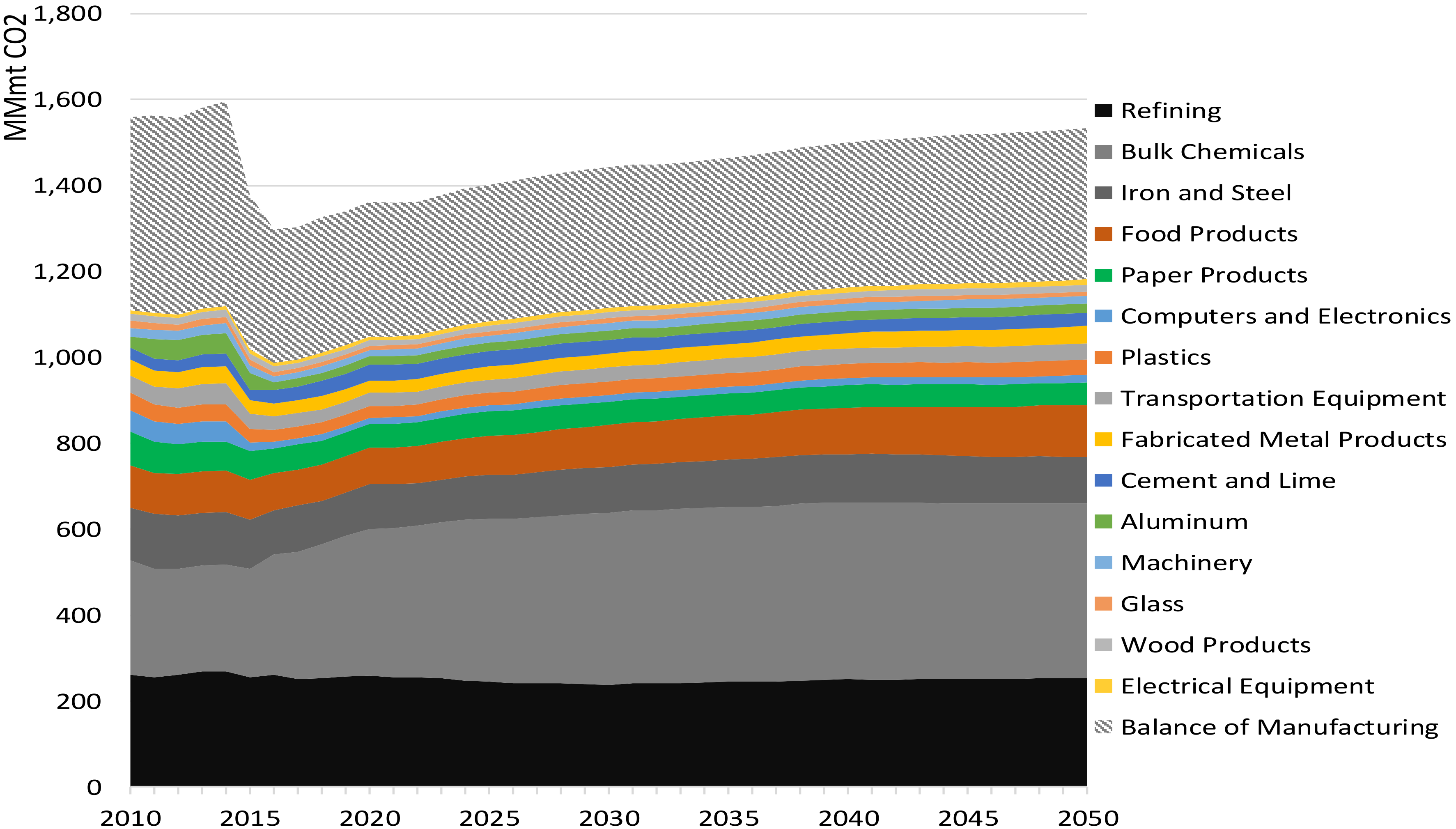
U.S. Mfg CO2 Emission: AEO 2018 RC



EIA Annual Energy Outlook 2018 Reference Case (http://www.eia.gov/forecasts/aeo/)

What we did talk about

Our expectations for large-scale industrial sector transformations must reflect the conditions industry faces such as:

1. Manufacturing Investments and Technology Deployment
2. Technology and Policy that influence Industry's Decarbonization technology options.
3. Modeling Decarbonization Pathways: Forecasting versus Scenarios

Manufacturing Investments and Technology Deployment Perspectives

Investment Decision Making Conditions

1. Competition versus Regulation
2. Variability versus Uncertainty
3. Short-term, Near-term, and Long-term perspectives
4. Risk Aversion & Market Share
5. Capital Recovery wrt Variability versus Uncertainty

Technology Deployment

1. Mature versus Emerging Markets
2. Rebound Effects
3. Unintended Consequences

Decarbonization Technology Options/Pathways

Technology Pathways

1. Electrification
2. Decarbonized fuels
3. Backstop Technologies
   I. CO_2 Capture (CC)
      1. Concentrated Point Source (\$20-\$40/ton CO_2)
      2. Dilute Point Source (\$40-\$200/ton CO_2)
      3. Direct from Atmosphere (\$100/ton CO_2)
4. Carbon re-use, utilization, storage, and all the above

Decarbonization: Sectorial Considerations

What sector is likely to decarbonizes first?

I. Buildings (residential & commercial)
II. Transportation
III. Electricity
IV. AND Industrial

What Industrial sectors are likely to decarbonizes first?

I. Iron and Steel, Aluminum, Paper, or durable goods manufacturing?

What end-uses are likely to decarbonizes first?

I. Cross-cutting end-uses: Boilers? Process Heating?

Decarbonization Policy & Barriers to Address

Decarbonization Goals must be realistic: Responsible, Equitable, Effective, Efficient, and implementable.

Is a global carbon tax realistic?

If not, we must address emissions leakage, offshoring, and Stranded Assets like:

1. Oil, coal, and Natural Gas Reserves
2. Infrastructure, Industrial Capacity

And we must not "strand": trade relations, supply chains, AND economic stability.

While protecting our natural ecosystems.

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Improving how we use models to inform policy

Model category options

1. Economic Models: CGE, KLEMs, microeconomic production (supply), consumer choice (demand), etc.
2. Physical Models: Simple accounting, MARKAL, Liner Program (LP), Non-LP, etc.

Model's Objective Functions

1. Economic Models: Maximize Welfare (e.g., maximize GDP growth)
2. Physical Models: Balance resources to meet demand.

Alternative could be:

A. maximize climate stabilizing goals (e.g., Clean Energy/Total Energy)?
B. Productivity metrics (e.g., Production/Energy)

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Improving how we communicate model results

Precisely incorrect (Forecasts) versus Vaguely Correct-ish (Scenarios)

Forecast Examples:

1. NEMS side cases
2. Wisdom Index

Scenario Examples:

1. Autonomous Vehicles and Rebound Affects
2. Biomass allocations in a carbon constrained future

"Believability Wedges" rather than "Uncertainty Bounds"?

When our audiences haven't been trained in uncertainty analysis?

What I had planned to talk about Slides

End-use energy consumption sub-sector level (e.g., iron and steel, refining, chemicals, etc.

Presentation Outline

Manufacturing End-Use Energy Consumption: Aggregate and Subsector

U.S. DOE, EIA, Manufacturing Energy Consumption Survey (MECS)

Manufacturing Subsector: Electricity to Fuel Cost Ratio, Energy and Materials Productivity ($Cost/$ Value Add)

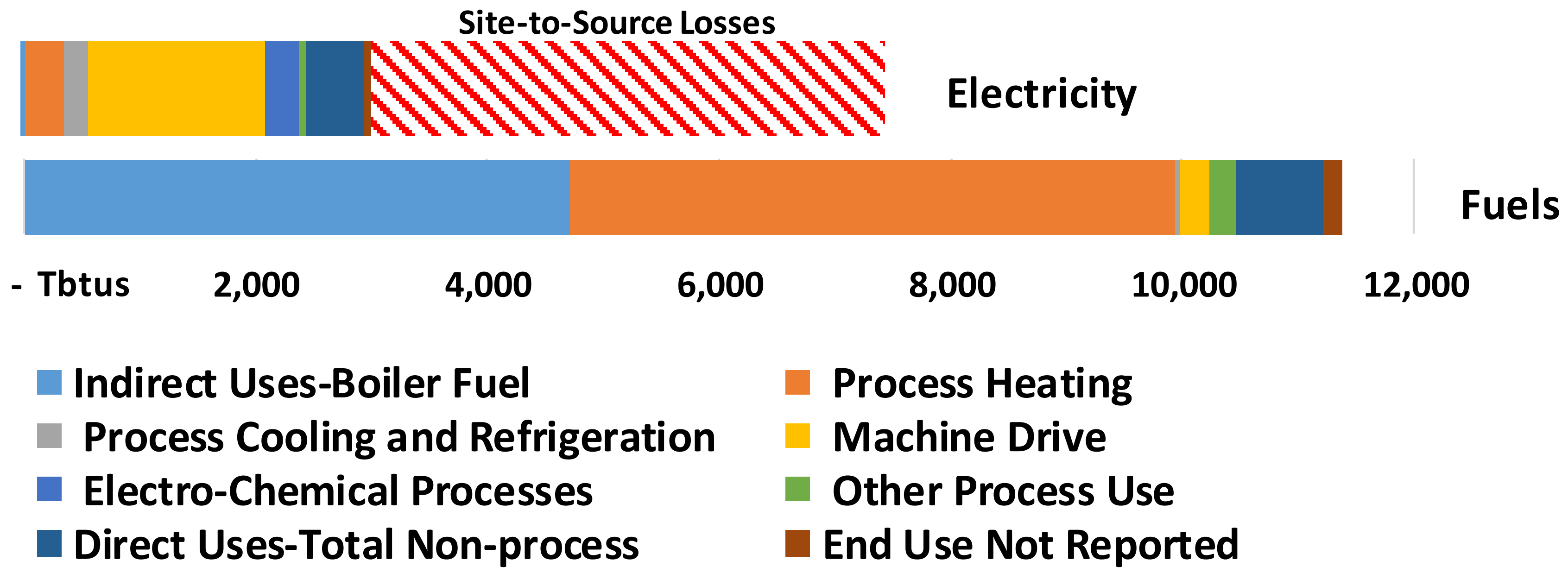
U.S. Census, Annual Survey of Manufactures Data

Time-Series Analysis: Key Economic & Productivity Metrics

Historic U.S. Industrial Sector Energy Intensity

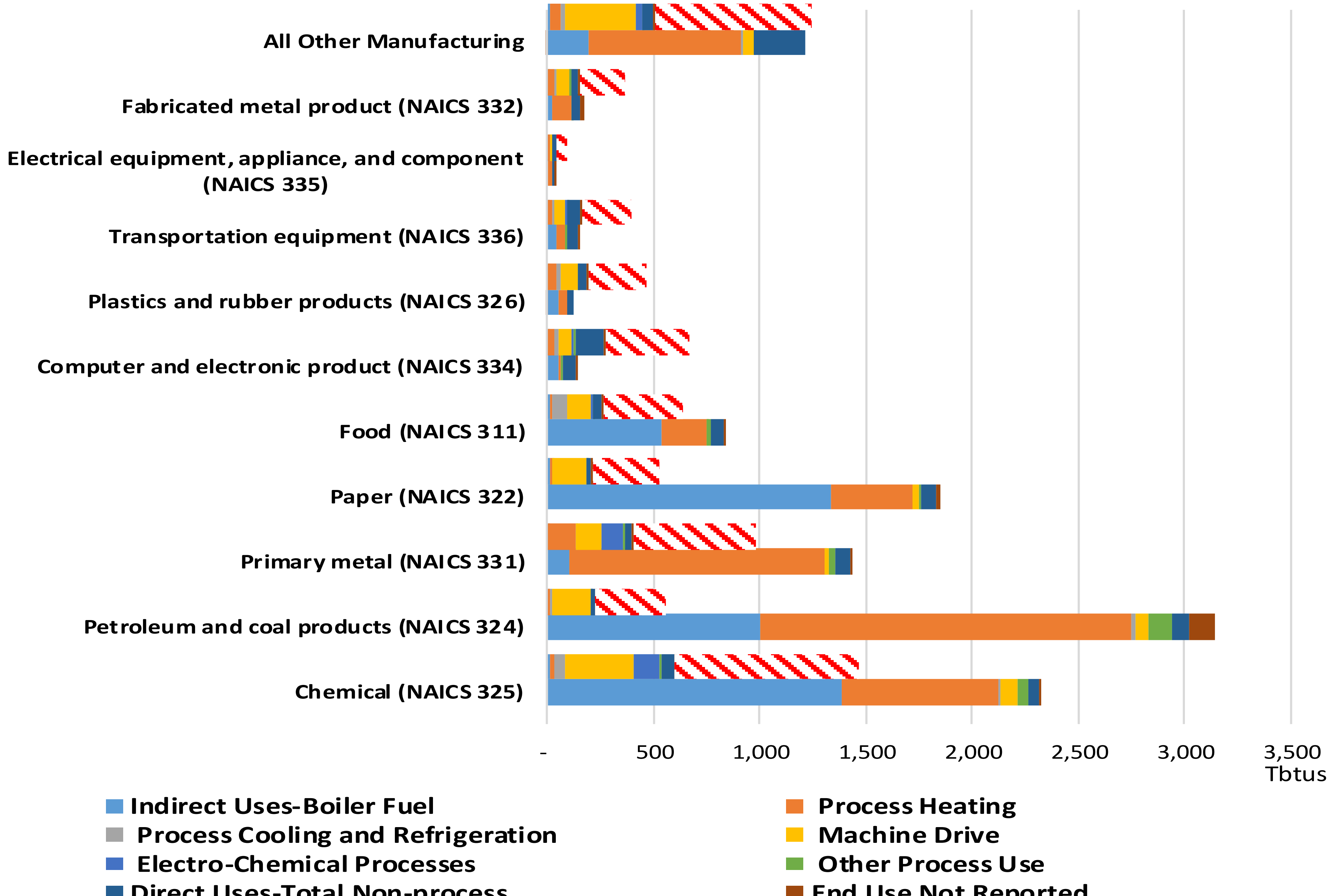
Opportunities

Manufacturing End-Use Energy Consumption (MECS 2010)



Data: U.S. DOE, EIA, Manufacturing Energy Consumption Survey (MECS), 2010 data

Mfg. Subsector End-Use Energy Consumption



Data: U.S. DOE, EIA, Manufacturing Energy Consumption Survey (MECS), 2010 data

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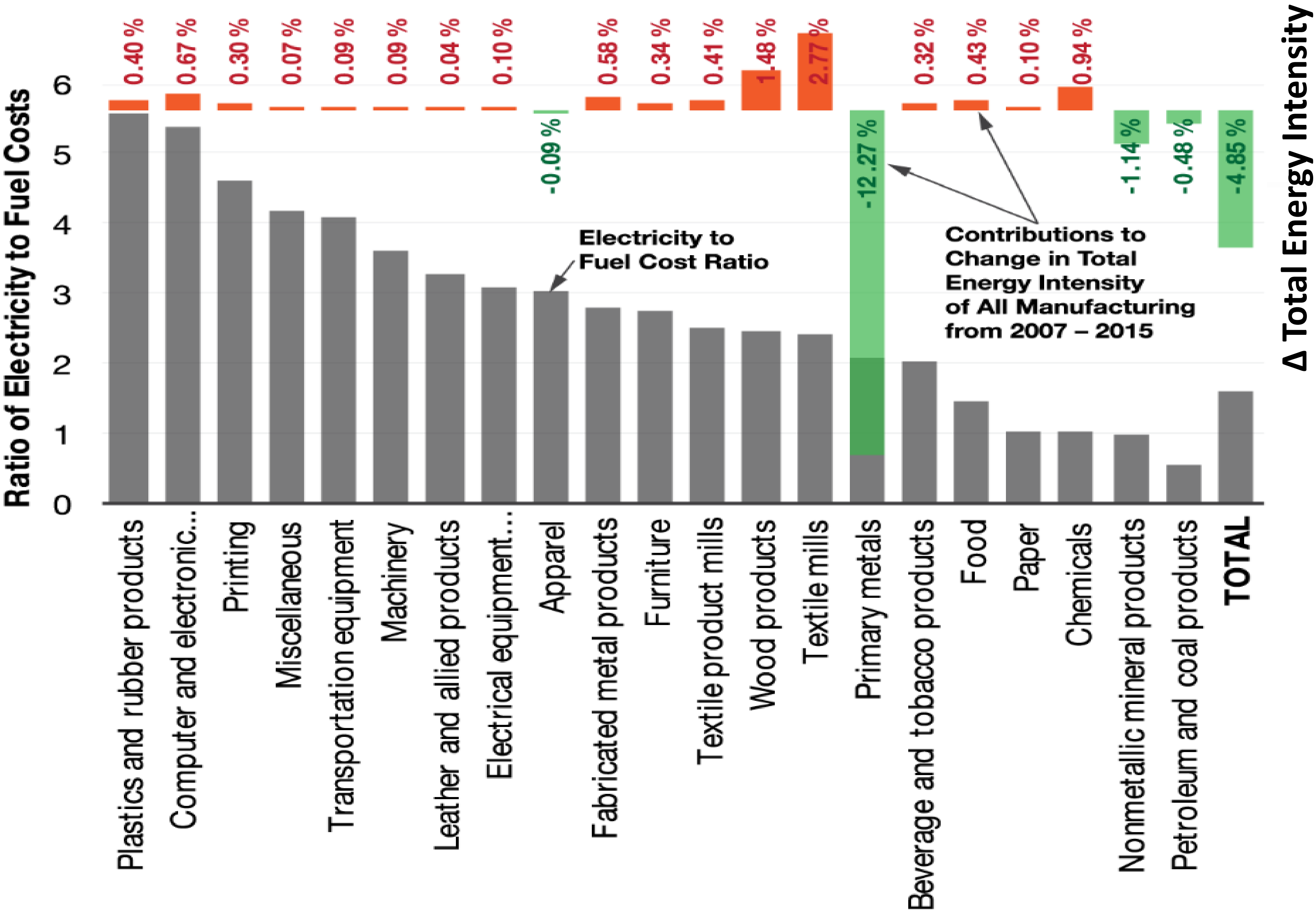
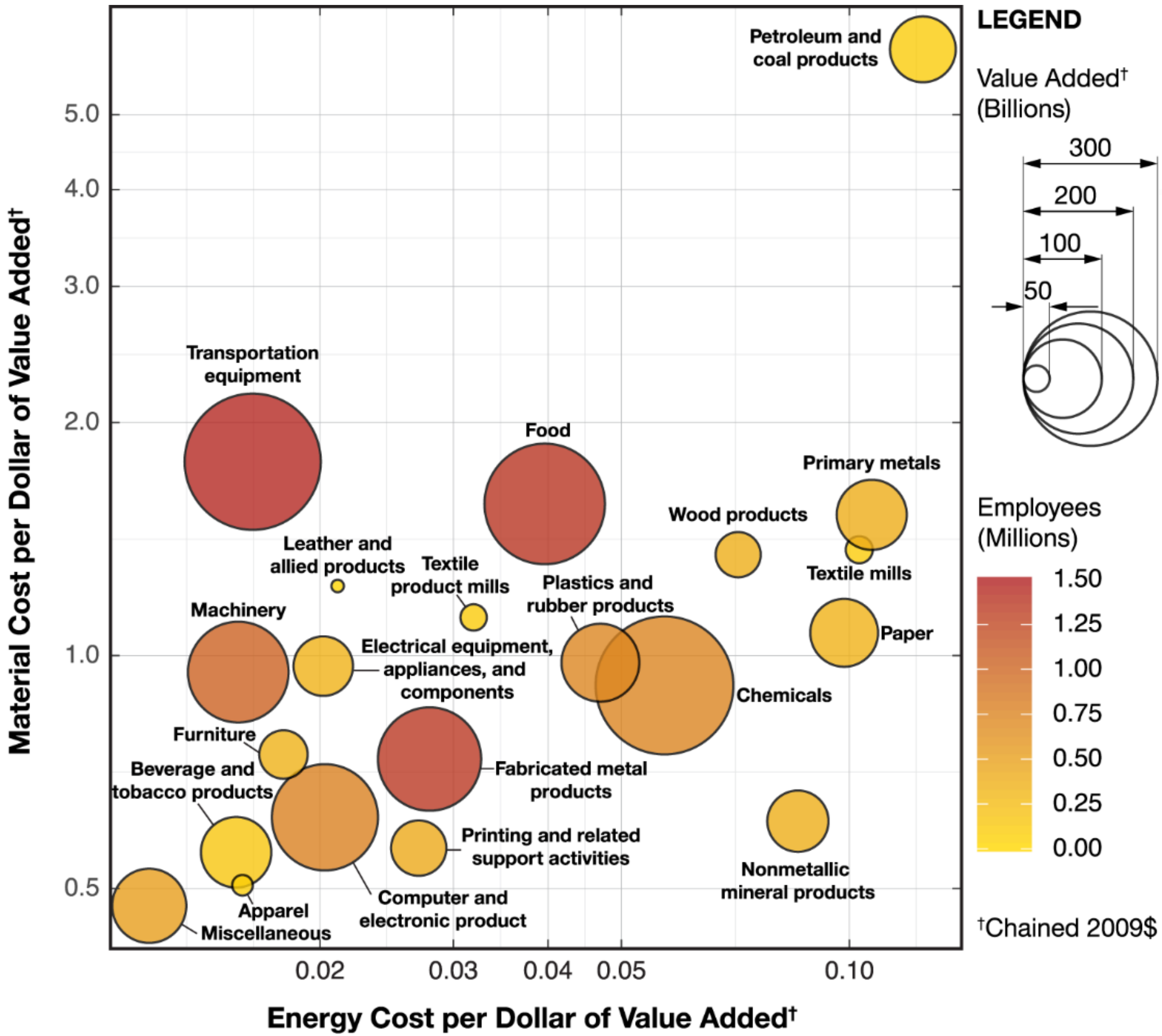


Data: U.S. Census, Annual Survey of Manufactures: 2007-2015 Dataset

Time Series Analysis
Value of Shipments (VOS) and GDP Definition

Term	Definition
Gross Domestic Product (GDP)	Market value of all final goods and services produced
Value of Shipments (VOS)	Net selling values (exclusive of freight and taxes) of all products shipped plus miscellaneous receipts
Value-Add (VA)	Value of Shipments (VOS) minus the cost of energy, materials, and contract work



Data: U.S. Census, Annual Survey of Manufactures: 2007-2015 Dataset

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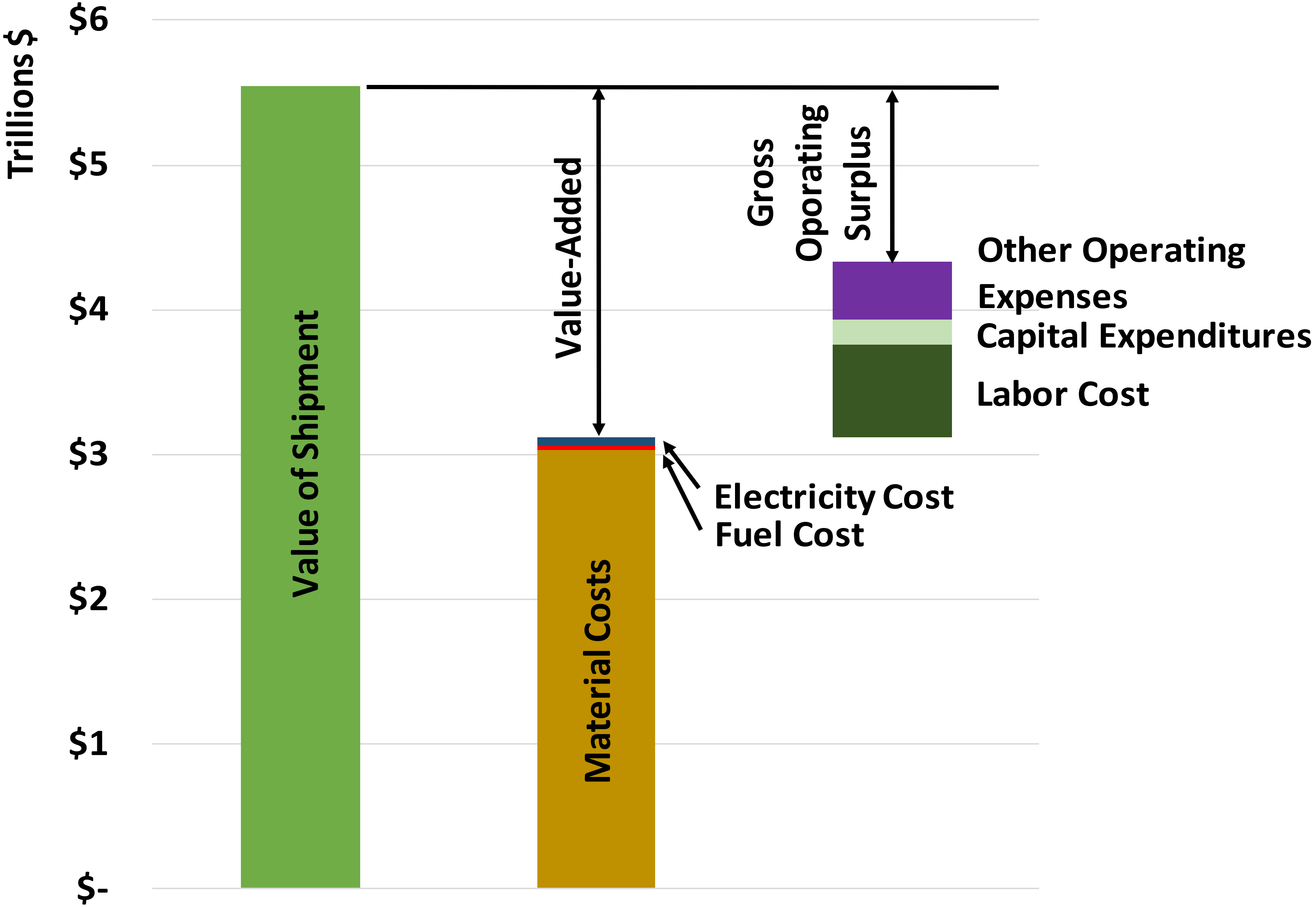
Annual Survey of Manufactures year 2015



Data: U.S. Census, Annual Survey of Manufactures: 2007-2015 Dataset

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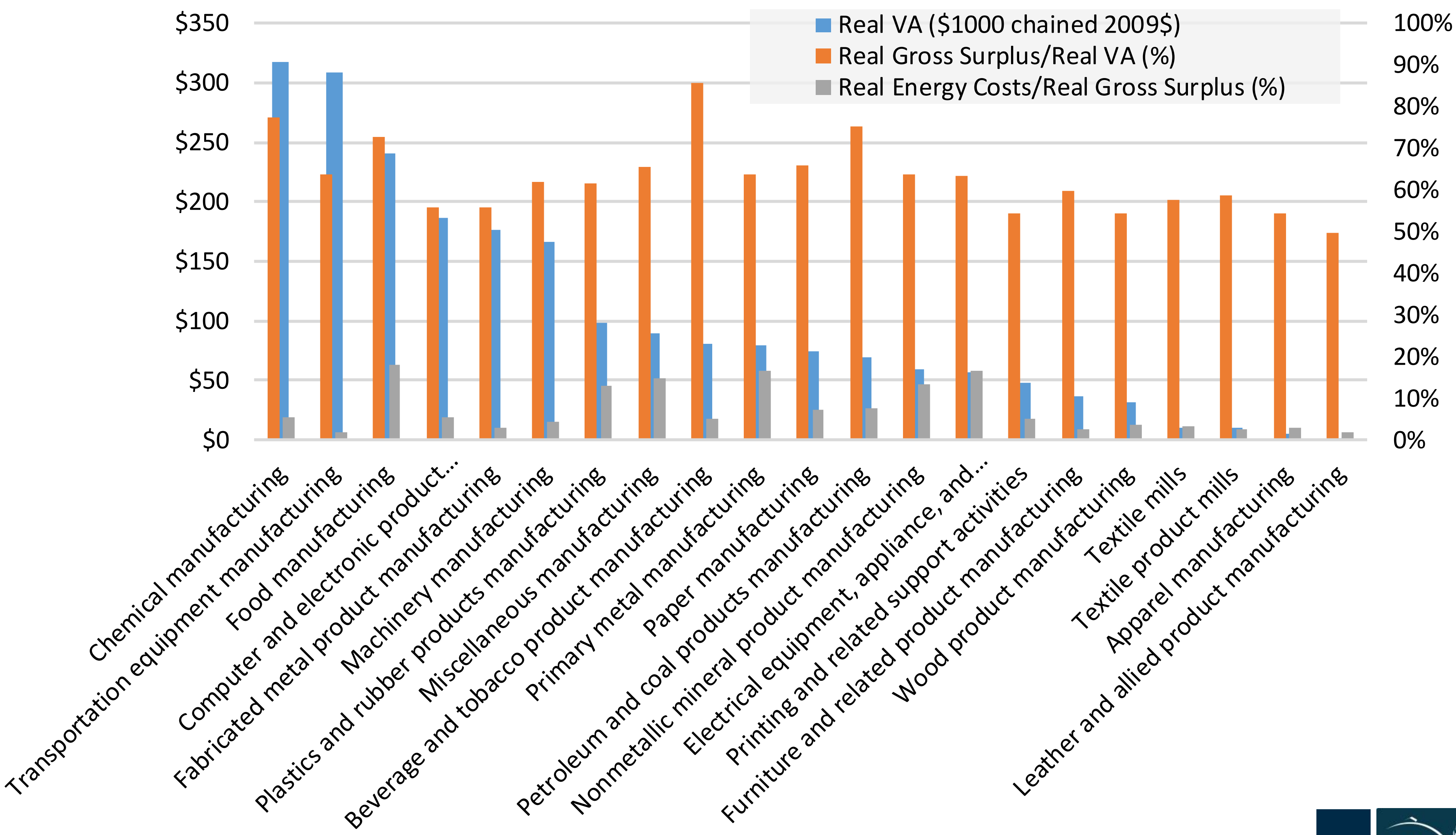
U.S. Manufacturing Value Add, Gross Surplus, and Energy Costs



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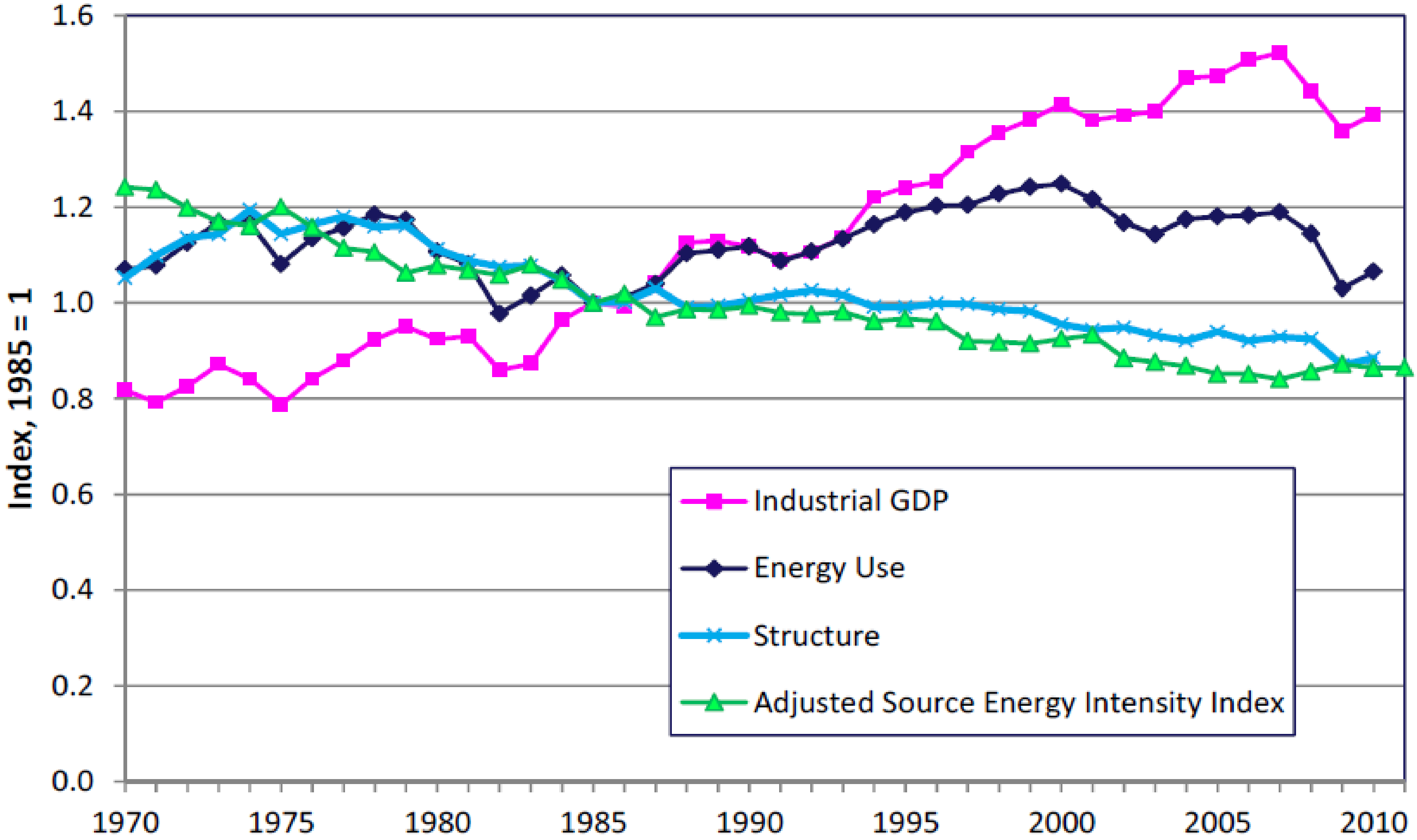
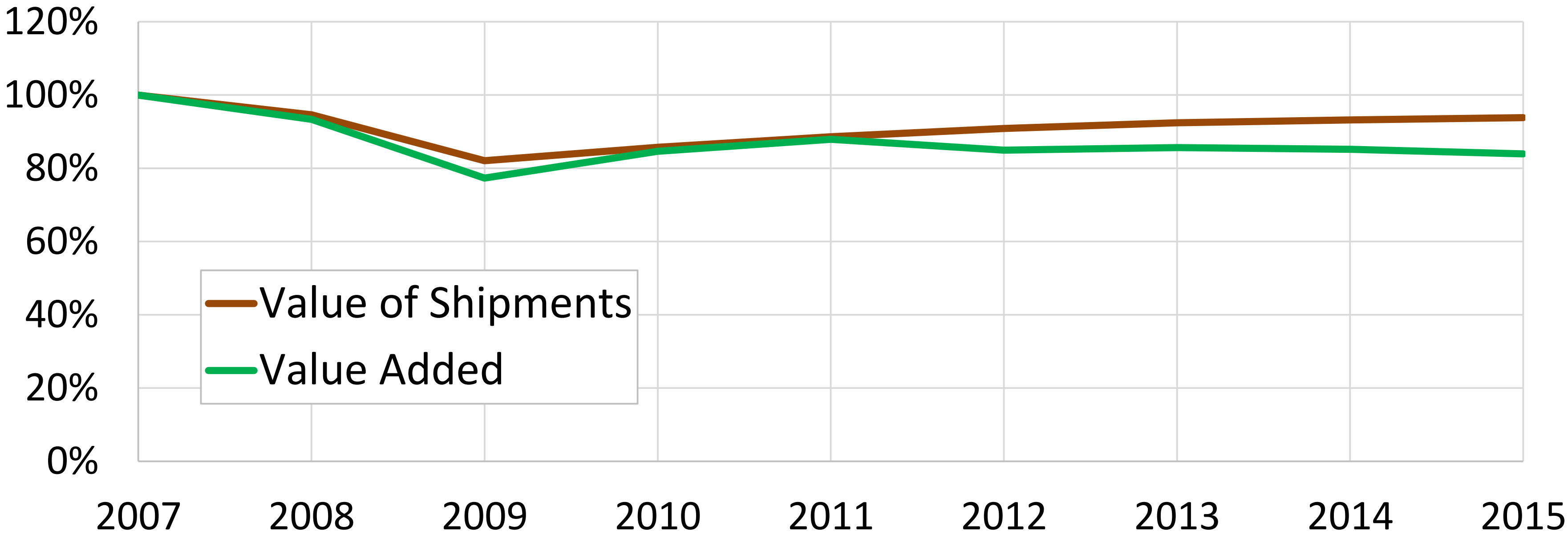
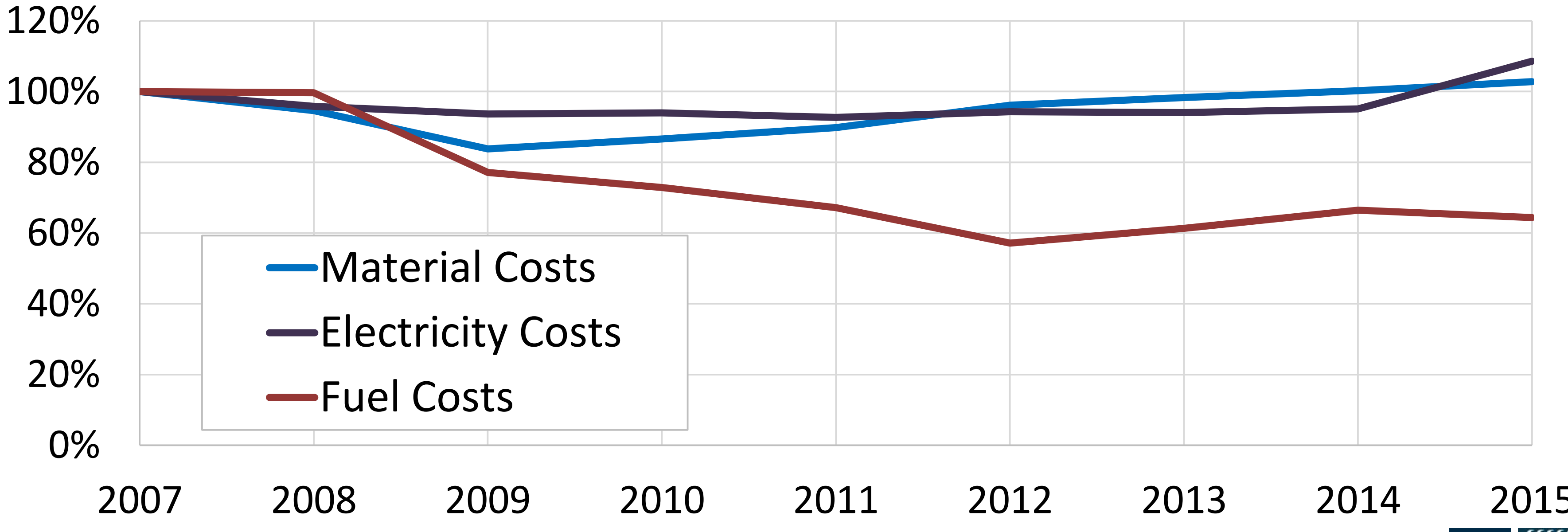
Historic U.S. Industrial Sector Energy Intensity and Related Metrics



http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22267.pdf

Time-Series Analysis



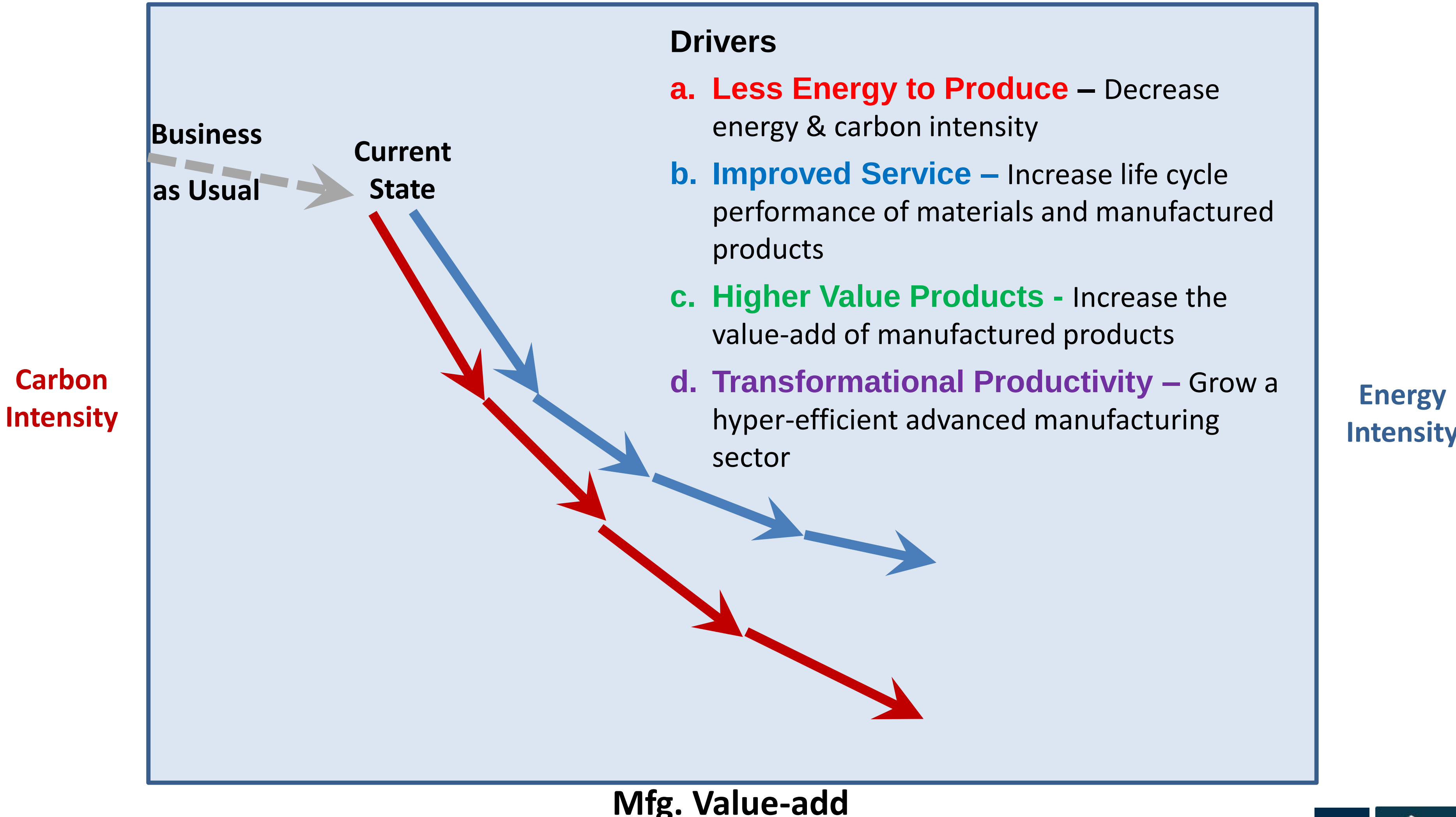


Data: U.S. Census, Annual Survey of Manufactures: 2007-2015 Dataset

Intensity and Productivity Metrics

Metric	Calculation	Units
Energy Intensity	Energy Inputs / Economic Output	$\frac{MMBtus}{\$_{GDP,VOS,VA}}$ $\frac{\$_{Energy}}{\$_{GDP,VOS,VA}}$
Energy Productivity	Economic Output / Energy Inputs	$\frac{\$_{GDP,VOS,VA}}{MMBtus}$ $\frac{\$_{GDP,VOS,VA}}{\$_{Energy}}$
Materials Intensity	Materials Expenditures / Economic Output	$\frac{\$_{Materials}}{\$_{GDP,VOS,VA}}$
Materials Productivity	Economic Output / Materials Expenditures	$\frac{\$_{GDP,VOS,VA}}{\$_{Materials}}$

Moving Towards High Energy & Carbon Productivity



Drivers

a. **Less Energy to Produce** – Decrease energy & carbon intensity

b. **Improved Service** – Increase life cycle performance of materials and manufactured products

c. **Higher Value Products** - Increase the value-add of manufactured products

d. **Transformational Productivity** – Grow a hyper-efficient advanced manufacturing sector

Opportunities

Opportunity	Definition
Energy Conservation	Reduce energy consumption by reducing energy service
Energy Efficiency	Reduce energy consumption but maintaining constant
Materials Efficiency	Reduce embodied life-cycle energy through better designs
Advanced Materials	Improve manufacturing and product use-phase energy
Fuel Switching	Same or improved energy service with lower emissions

Discussion Topics

How should productivity metrics be used?

Which metrics are best for:

Policy Makers? Technology Analysts? Industry Leaders?

What does productivity mean for U.S. Manufactures?

And the U.S. economy?

Do historic trends predict our future?

Can we accelerate environmental goals?

What pathways can we expect of U.S. manufacturers?

Considering:

Diversity of sectors, processes, and products?

Innovation & global competitiveness?

How best to overcome economic and technical constraints?

Sustainable productivity growth?

Sustainability?

Thank You

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A Techno-Economic Assessment of Energy Efficiency and Carbon Capture in U.S. Petroleum Refineries

Presenter:

William R. Morrow, III – Lawrence Berkeley National Laboratory

Co-Author:

John J. Marano, JM Energy Consulting, Inc., Gibsonia, PA

Yuan Yao – North Carolina State University

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U.S. Petroleum Refinery Sector: Energy Efficiency Modeling†

- Objective: Estimate Energy Efficiency Supply Curves

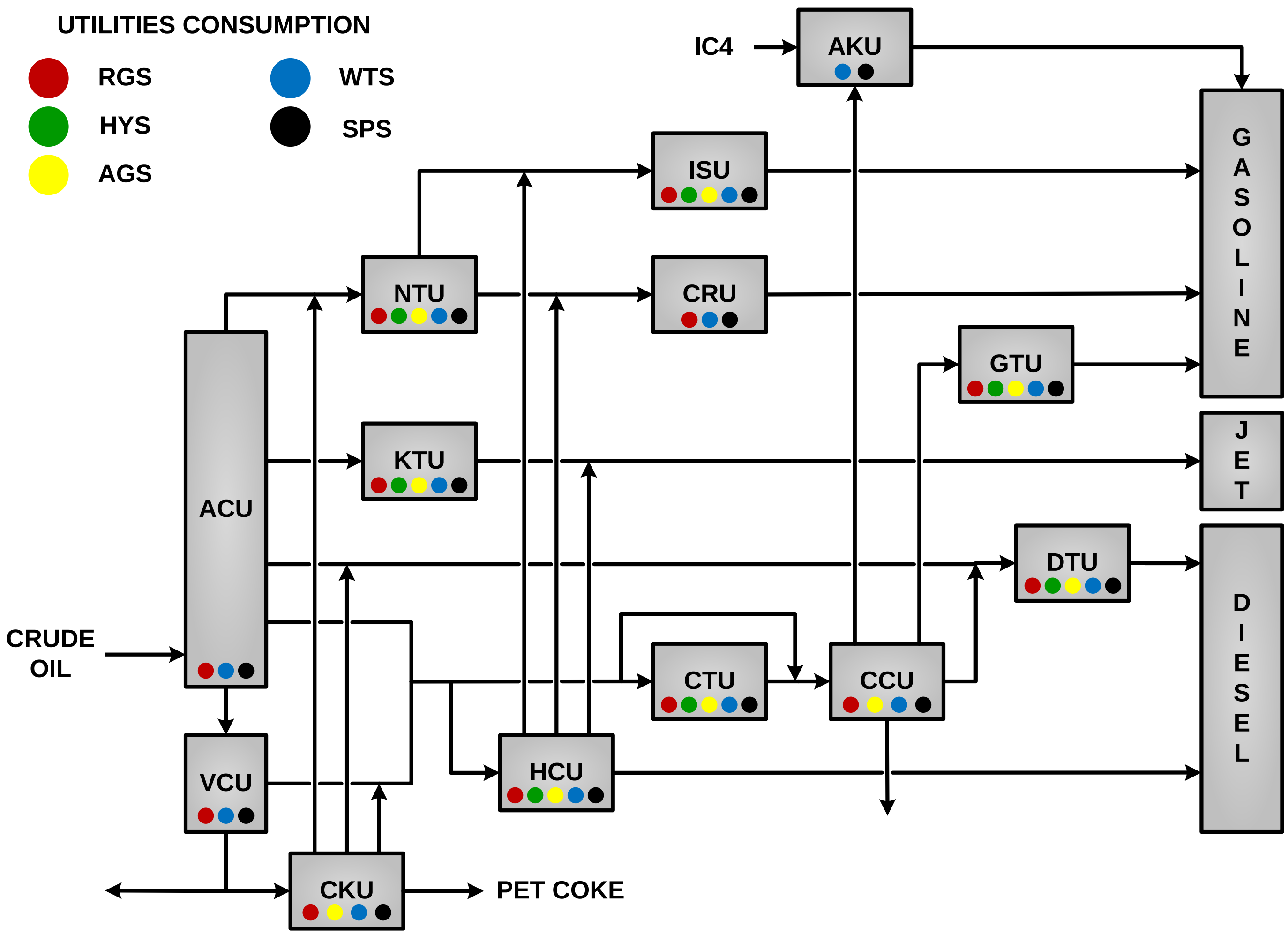
  Synthesizes refinery data, costs estimations, chemical/process engineering experience, and expert judgment to estimate the current potential, and costs, for energy efficiency across the entire U.S. petroleum refining capacity.

- Methodology: Refinery Sector Modeling
  - Product, carbon, and energy balancing across major processing units, including utilities (fuel, steam, electricity, and hydrogen).
  - Capture the integrated nature of petroleum refining sector
  - Reflects diminishing benefits as measures are sequenced through the sector (lowest cost first reduces the benefits of subsequent, more costly, inter-related measures).

- Key outcome: process and aggregate refinery energy conservation supply curves

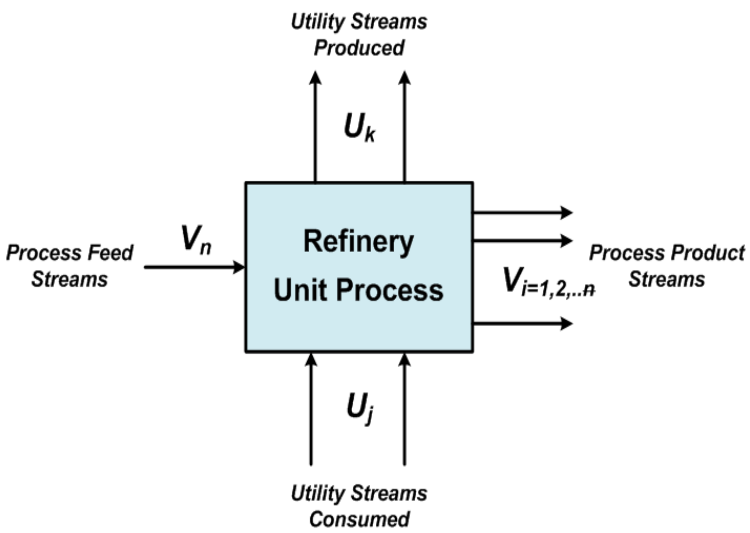
† Assessment of Energy Efficiency Improvement in the United States Petroleum Refinery Industry – LBNL report 6292E
Authors: William R. Morrow, III, John Marano, Jayant Sathaye, Tengfang Xu

U.S. Petroleum Refinery Sector:
Aggregate Sector Model ‡



‡ Morrow III, W. R., J. Marano, et al. (2015). "Efficiency improvement and CO2 emission reduction potentials in the United States petroleum refining industry." Energy 93, Part 1: 95-105.

U.S. Petroleum Refinery Sector: Aggregate Sector Model ‡



Notional Refinery Model Framework

$V_{im}^{(out)} = y_{ijm} \, V_{jm}^{(in)}$; $\sum_n y_{ijm} \neq 1$ Eq. 1 – Mass Balance within process unit

where:
- $V_{im}^{(out)}$ - material flow of product *i* leaving unit process *m*, on volume basis
- y_{inm} - yield of product *i* relative to feed *j* to unit process *m*
- $V_{jm}^{(in)}$ - material flow of a feed *j* entering unit process *m*

$V_{jn}^{(in)} = x_{hjnm} \, V_{jm}^{(out)}$; $\sum_n x_{jnm} = 1$ Eq. 2 – Mass Balance across process unit

where:
- $V_{jn}^{(in)}$ - material flow of stream *j* entering unit process or product pool *n*
- x_{jnm} - deposition factor of stream *j* to unit process or pool *n* relative to process *m*
- $V_{jm}^{(out)}$ - material flow of a product stream *j* from unit process *m*

$U_{km}^{(in)} = c_{hkjm} \, V_{jm}^{(base)}$ Eq. 3 – Energy Balance within process unit

where:
- $U_{km}^{(in)}$ - consumption of utility *k* associated with unit process *m*
- c_{kjm} - consumption factor of utility *k* relative to stream *j* associated with unit process *m*
- $V_{jm}^{(base)}$ - material flow of a feed *j* entering unit process *m* (*i.e.* stream *j* is the basis for utility data for unit process *m*)

$U_{km}^{(in)} = c_{hkjm} \, U_{jm}^{(base)}$ Eq. 4 – Energy Balance across utility unit

where:
- $U_{km}^{(in)}$ - consumption of utility *k* within utility system *m*
- c_{kjm} - consumption of utility *k* relative to utility production *j* associated with utility system *m*
- $U_{jm}^{(base)}$ - utility *j* produced by utility system *m* (*i.e.* utility *j* is the basis for utility data for utility system *m*)

‡ Morrow III, W. R., J. Marano, et al. (2015). "Efficiency improvement and CO2 emission reduction potentials in the United States petroleum refining industry." Energy 93, Part 1: 95-105.

Estimated Energy Consumption for the U.S. Petroleum Refining Model circa.2010‡

Process	Throughput	Fuel (PJ, Primary)		Electricity (GWh, End-Use)	
	Million bbl/year	ISBL	OSBL	ISBL	OSBL
CDU	5,540	399	636	4,044	1,766
CKU	736	109	26	2,280	881
CTU	1,096	49	398	145	2,079
CCU	1,779	-822	103	5,653	5,103
HCU	478	93	474	61	2,268
DTU	1,040	52	246	151	1,188
KTU	579	29	57	404	424
NTU	1,111	94	92	162	390
CRU	961	303	115	949	1,459
ISU	146	6	28	21	9
GTU	694	56	225	99	701
AKU	205	0	42	5	604
Total Modeled Energy Consumption		368	2,443	13,975	16,873

Inside the battery limits (ISBL) – energy consumption within the processing unit
Outside the battery limits (OSBL) – energy consumption outside the processing unit but necessary to support the processing unit

‡ Morrow III, W. R., J. Marano, et al. (2015). "Efficiency improvement and CO2 emission reduction potentials in the United States petroleum refining industry." Energy 93, Part 1: 95-105.

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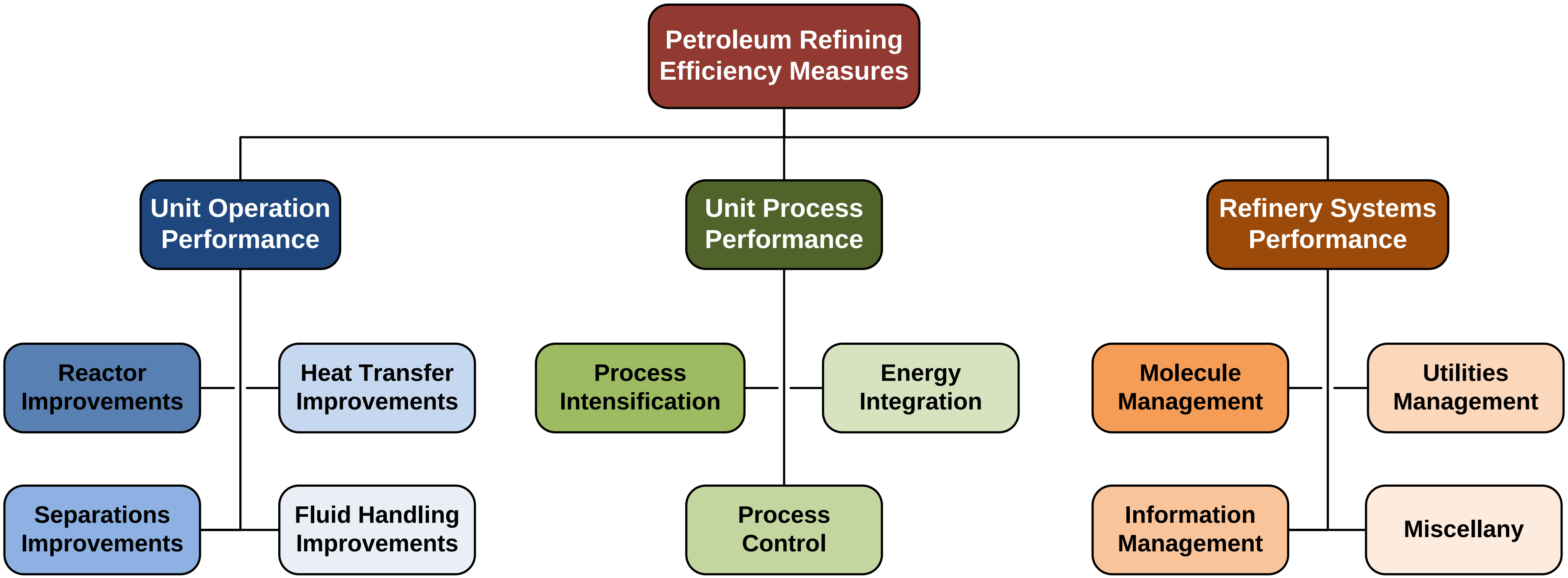
Efficiency Improvement Hierarchy ‡



$$CCE = \frac{I \times q + (M - B)}{ES}$$

Eq. 5 – Cost of Conserved Energy (CCE) for an energy-efficiency measure ($/GJ)

where:

I - *Added* Capital Cost, $

q - Capital Recovery Factor, yr^{-1}

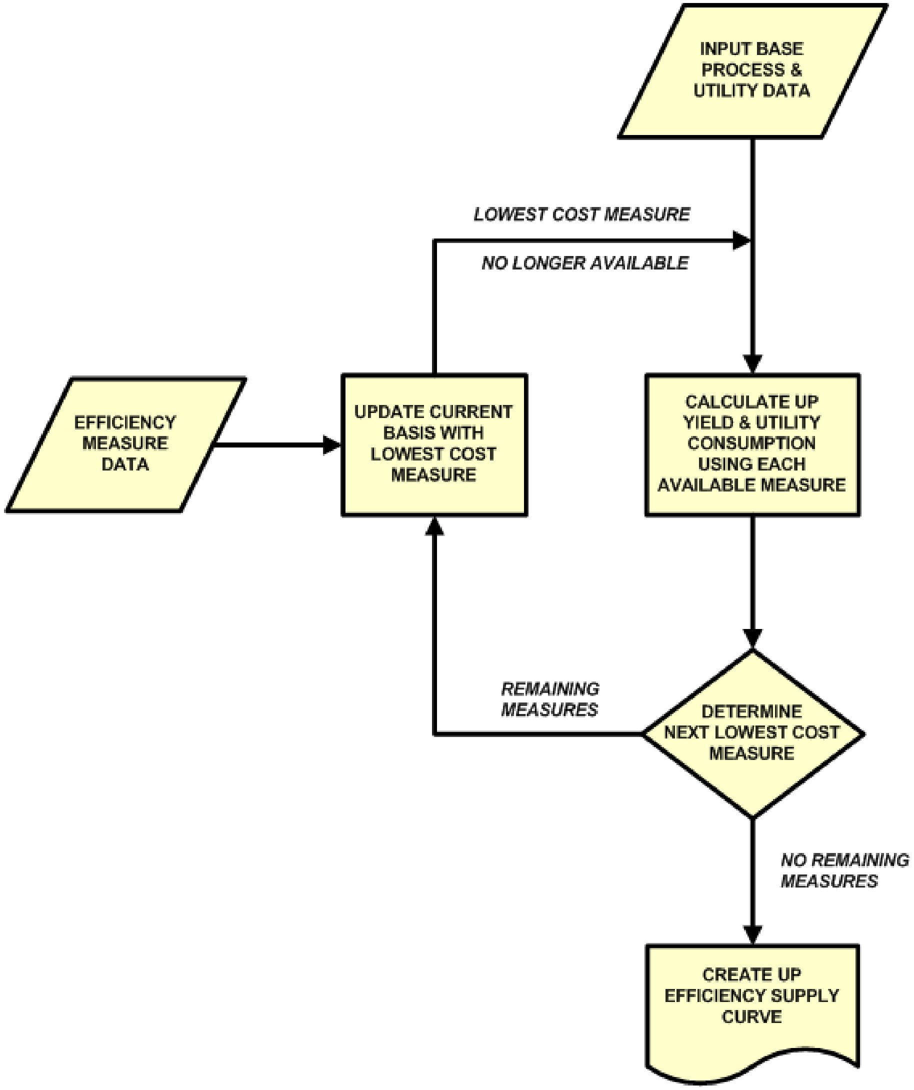
M - Non-Energy Annual increases in O&M costs, $

B - Annual decreases in O&M costs due to non-energy productivity improvements, $

ES - Annual Energy Savings, GJ/yr

‡ Morrow III, W. R., J. Marano, et al. (2015). "Efficiency improvement and CO2 emission reduction potentials in the United States petroleum refining industry." Energy 93, Part 1: 95-105.

Efficiency Supply Curve Solution Algorithm ‡



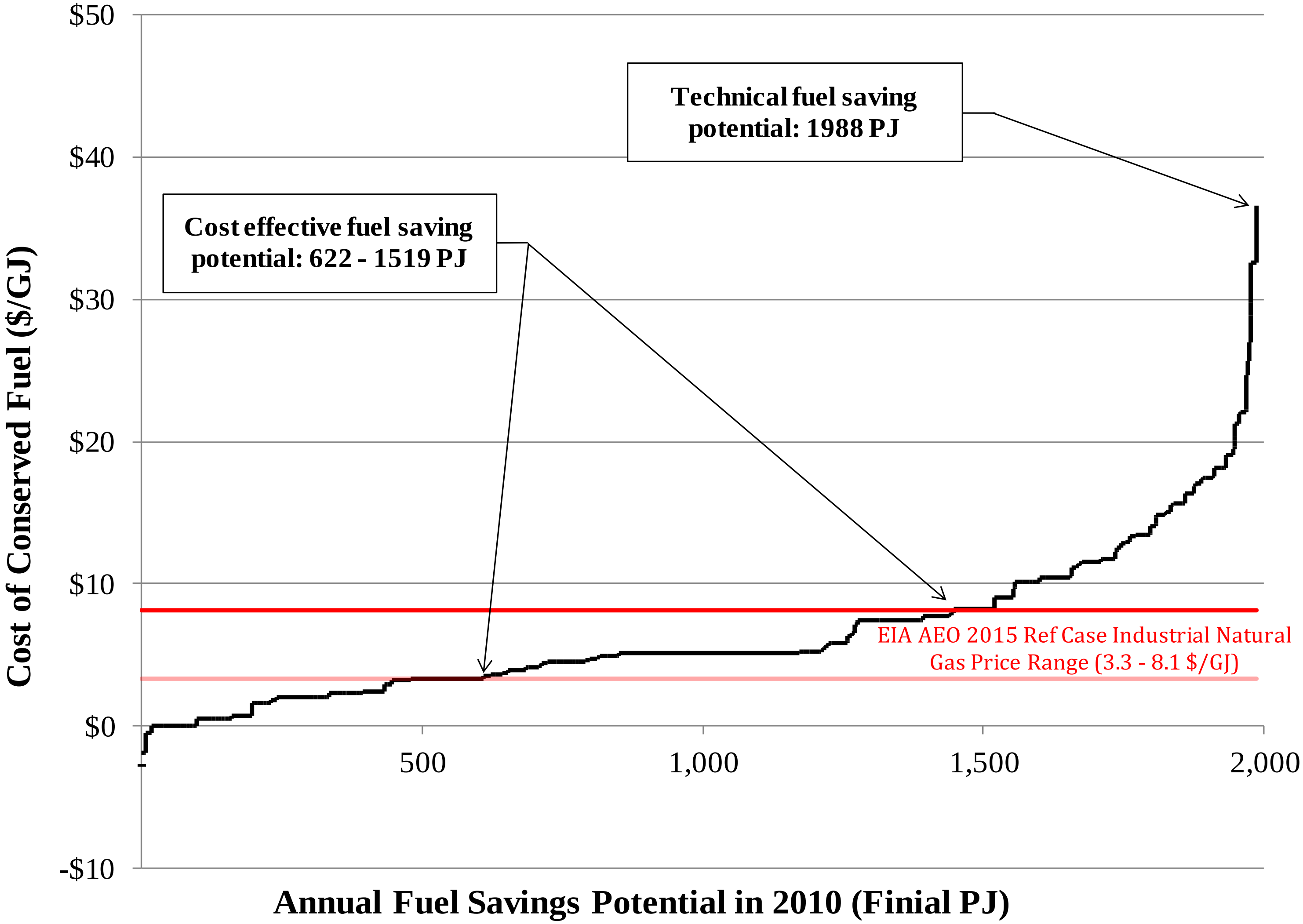
The supply curve is based on implementing measures starting with the lowest cost option and proceeding through to the highest cost option, and the cost of a given measure can be different if implemented earlier or later in the sequence.

For Example: If the process is poorly integrated and furnace efficiency measures are implemented first, the energy savings can be extremely large; however, if integration is done prior to furnace improvements, energy savings associated with furnace efficiency measures can be much smaller.

The order in which the measures are applied is not arbitrary!

‡ Morrow III, W. R., J. Marano, et al. (2015). "Efficiency improvement and CO2 emission reduction potentials in the United States petroleum refining industry." Energy 93, Part 1: 95-105.

Refining cost of conserved energy and energy saving potential (includes fuel & electricity) ‡



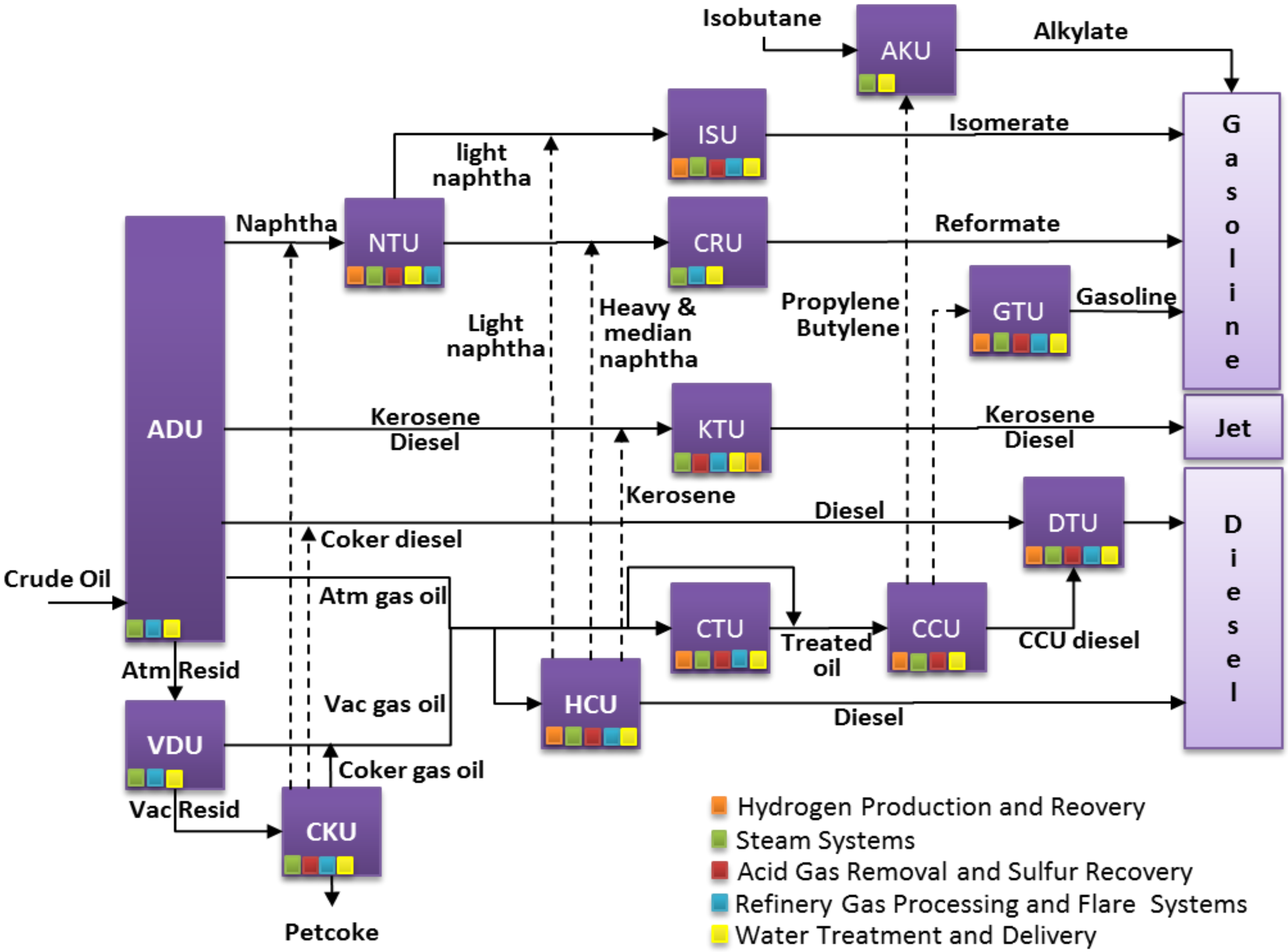
‡ Morrow III, W. R., J. Marano, et al. (2015). "Efficiency improvement and CO2 emission reduction potentials in the United States petroleum refining industry." Energy 93, Part 1: 95-105.

CO_2 & H_2 Questions ††

- How large is the potential of CC for capturing national CO_2 emissions from the U.S. refinery industry?
- How much is the cost of CO_2 capture for the refinery process?
- What is the design strategy?

‡ Yao Y., Marano J., Morrow W.R., Masanet E., (2017 – in review). "Quantifying Carbon Capture Potential and Cost of Carbon Capture Technology Application in the U.S. Refining Industry" International Journal of Greenhouse Gas Controls.

Refinery Energy Model



Representative process flow diagram for refinery

Energy End-Use

Distributed facilities:

- Fired heaters
- Pumps and compressors

Centralized facilities:

- Steam systems
- Hydrogen production

ADU: atmospheric distillation unit
VDU: vacuum distillation unit
CKU: coking unit
HCU: gas oil hydrocracking unit
CTU: catalytic hydrotreating unit
CCU: catalytic cracking unit
HCU: hydrocracking unit
DTU: high-severity distillate hydrotreating
KTU: low-severity distillate hydrotreating
GTU: gasoline hydrotreating
NTU: naphtha treating unit
CRU: catalytic reforming unit
ISU: isomerization unit
AKU: alkylation unit

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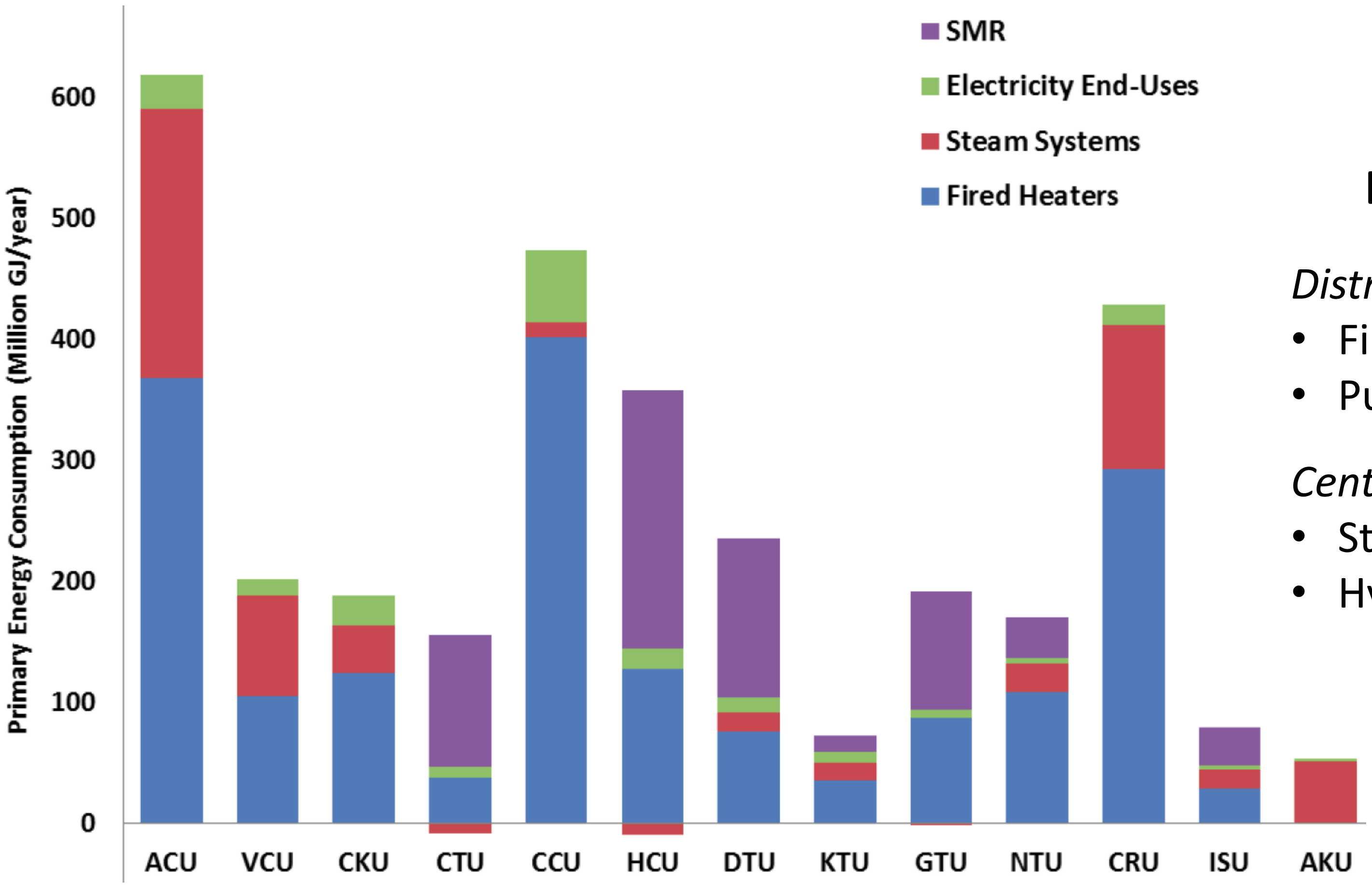
Primary energy consumption of unit processes in U.S. refineries (2014 year)

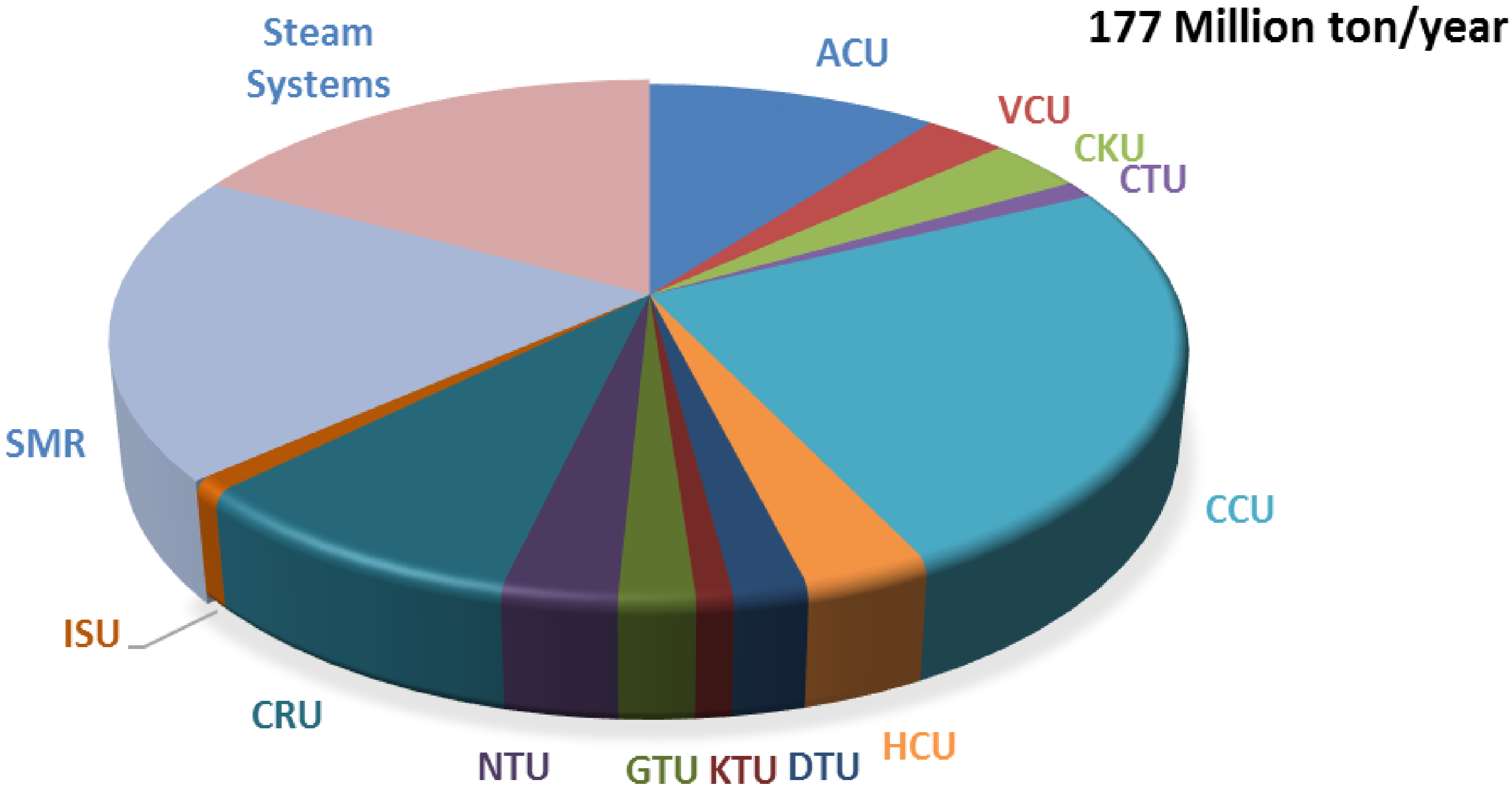


Energy End-Use

Distributed facilities:
- Fired heaters
- Pumps and compressors

Centralized facilities:
- Steam systems
- Hydrogen production

GHG Emissions Breakdown (2014)



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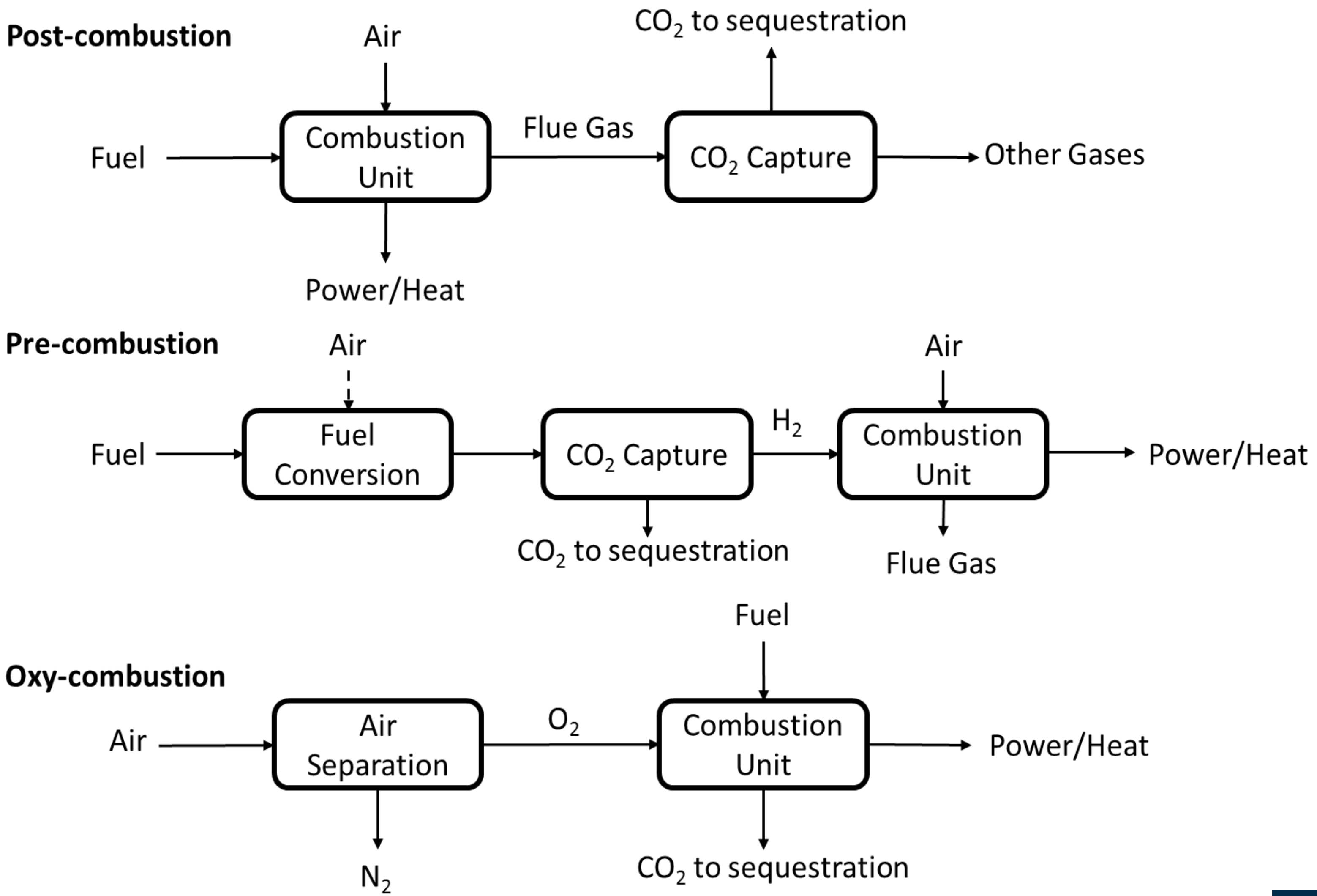
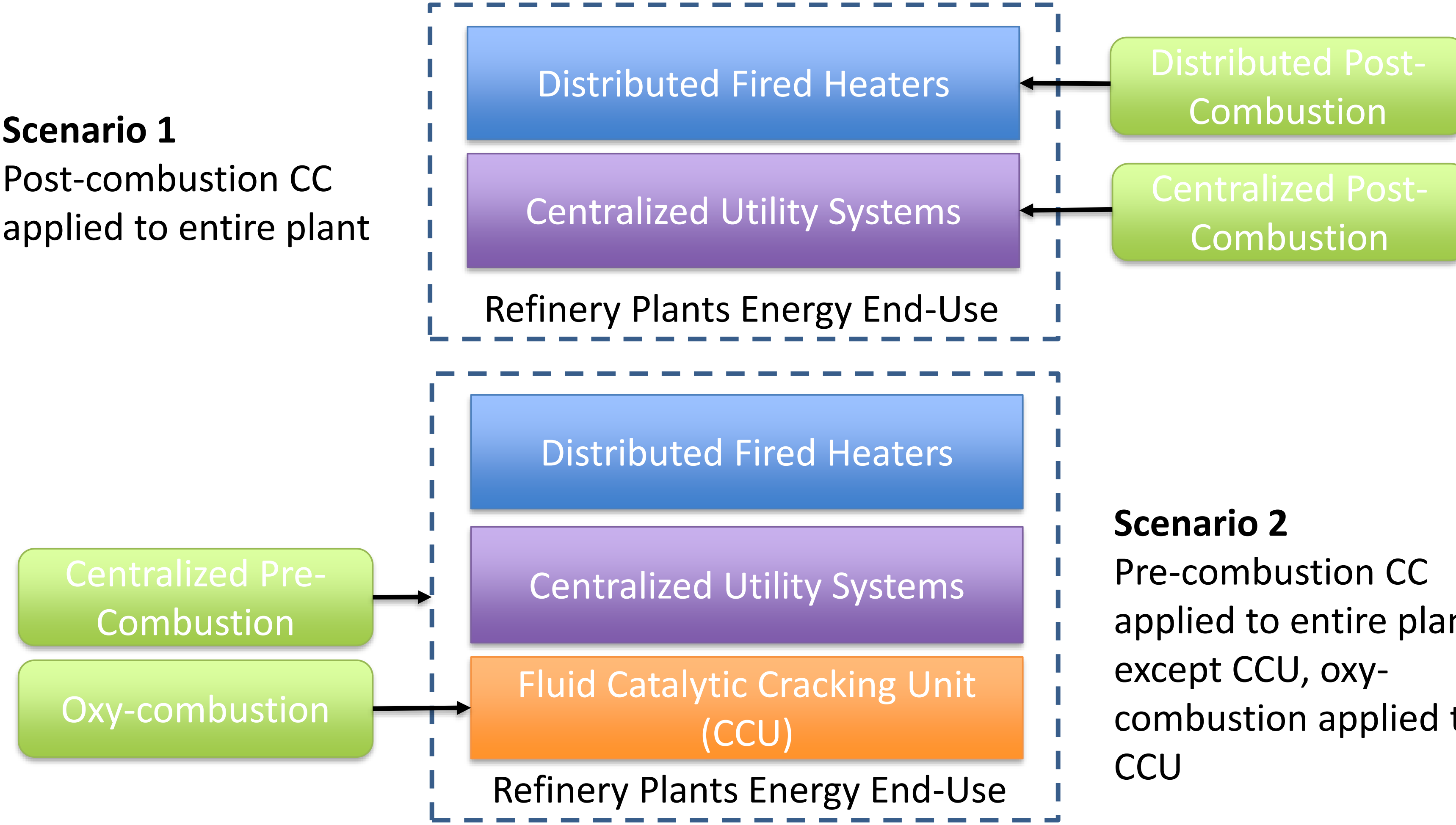
Carbon Capture System



Scenario Description

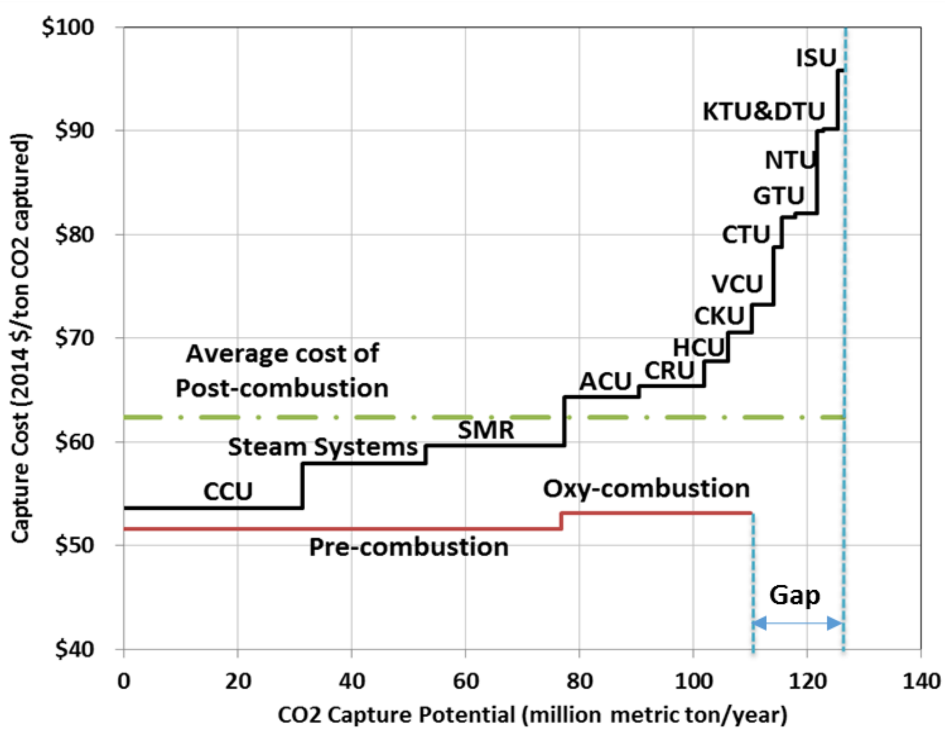
Scenario 1
Post-combustion CC applied to entire plant



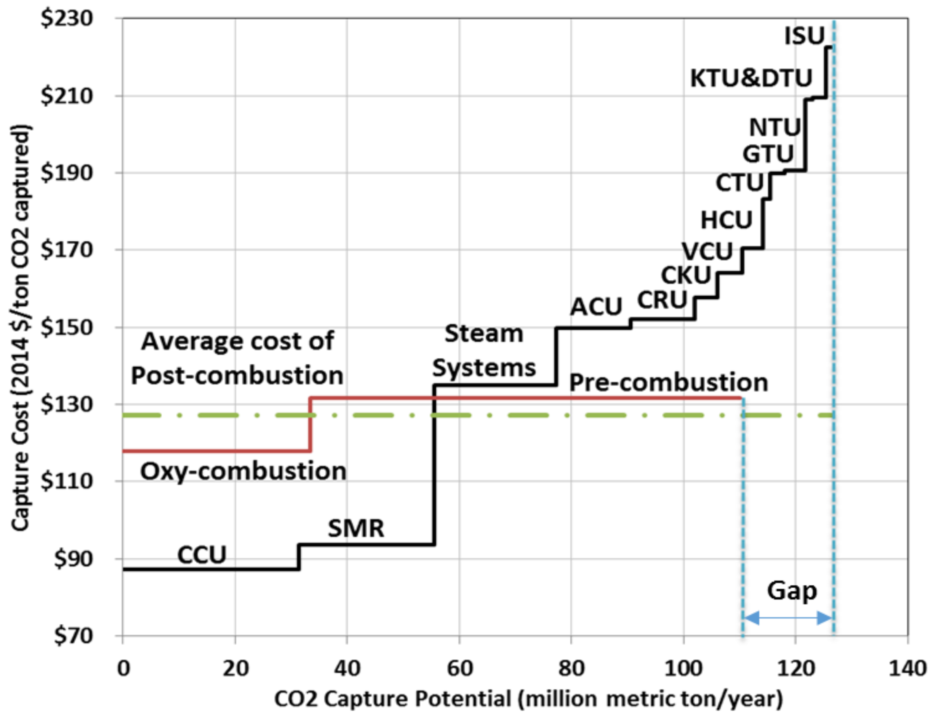
Scenario 2
Pre-combustion CC applied to entire plant except CCU, oxy-combustion applied to CCU

Cost and GHG Reduction Potential Results

Low Estimate



High Estimate



Post-Combustion Scenario

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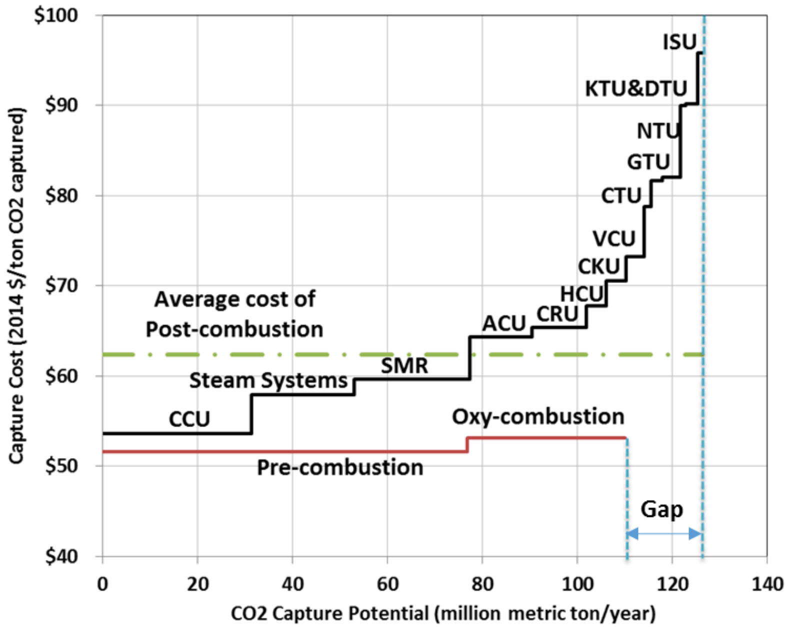
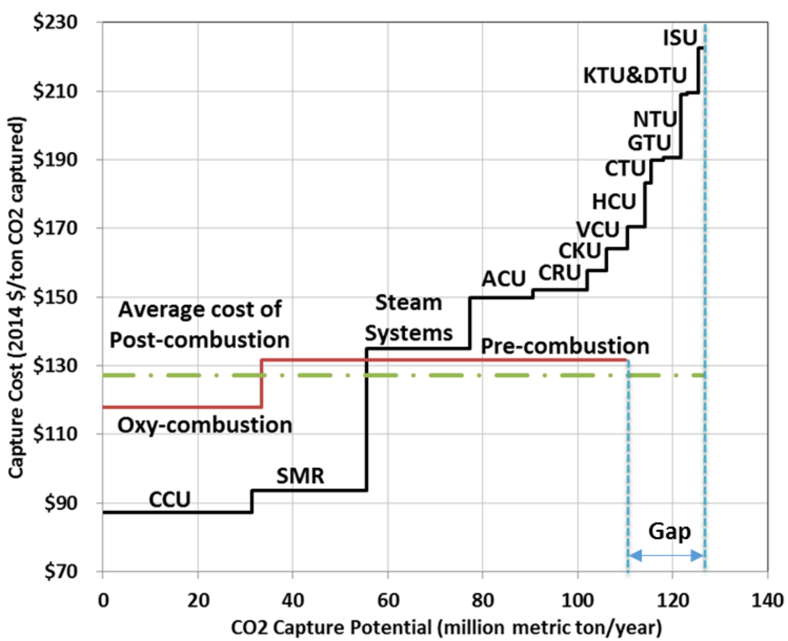
Low Estimate



High Estimate



Country/Region	Carbon Price (2014 US$/ton CO_2)
New Zealand ETS*	1
Mexican carbon tax	1 - 3
Regional Greenhouse Gas Initiative (RGGI)^	3
Japanese carbon tax	2
Tianjin Pilot ETS (China)	4
Shanghai Pilot ETS (China)	5
South African	5
Beijing Pilot ETS (China)	9
Guangdong Pilot ETS (China)	10
Icelandic carbon tax	10
French carbon tax	10
Shenzhen Pilot ETS (China)	11
California's Cap and Trade	11
U.K. carbon price floor	16
Australia Carbon Pricing Mechanism	22
British Columbia carbon tax	28
Finnish carbon tax	48
Swiss carbon tax	68
Norwegian carbon tax	4-69
Tokyo Cap-and-Trade	95
Swedish carbon tax	168

<$50/ton

*ETS: Emissions Trading Scheme
^RGGI: a market-based GHG reduction program covering CO_2 emissions from power plants in nine Northeast and Mid-Atlantic states of the US.

Conclusion

Centralized Hydrogen Utility

+ Carbon Capture

<u>+ H_2 fired furnaces</u>

A low cost option for CO_2 emissions reduction in U.S. Petroleum Refineries?

Supporting Slides for the Model Discussion

Model Discussion Slide Outline

1. Vaclov Smil Quotes
   – Wisdom Index
2. NEMS AEO CO2 Projection Scenarios
3. Biomass Allocations (electricity versus liquid fuels)
4. The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity
5. Autonomous Vehicle Scenarios

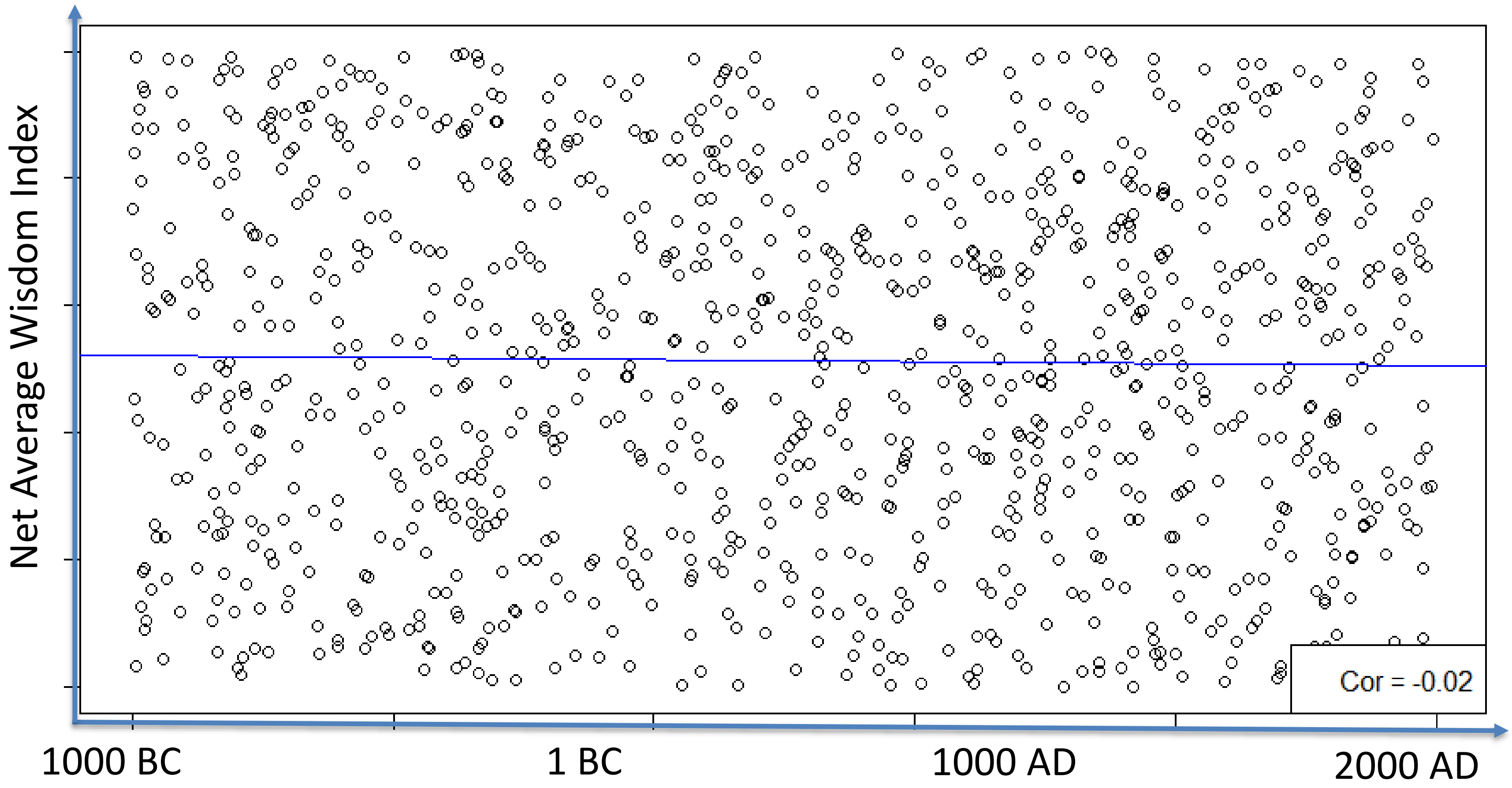
Vaclav Smil Quotes

Smil, V. (2000). "Perils of Long-Range Energy Forecasting: Reflections on Looking Far Ahead." Technological Forecasting and Social Change **65**(3): 251-264.

"…**we should abandon detailed quantitative point forecasts in favor of the decision analysis or contingency planning under a range of alternative (exploratory as well as normative) scenarios**."

Wisdom Index (for humor)

Human's Net Average Wisdom Index Peaked on June 6th 12 AD ~ 2:35 pm (PST) † ‡

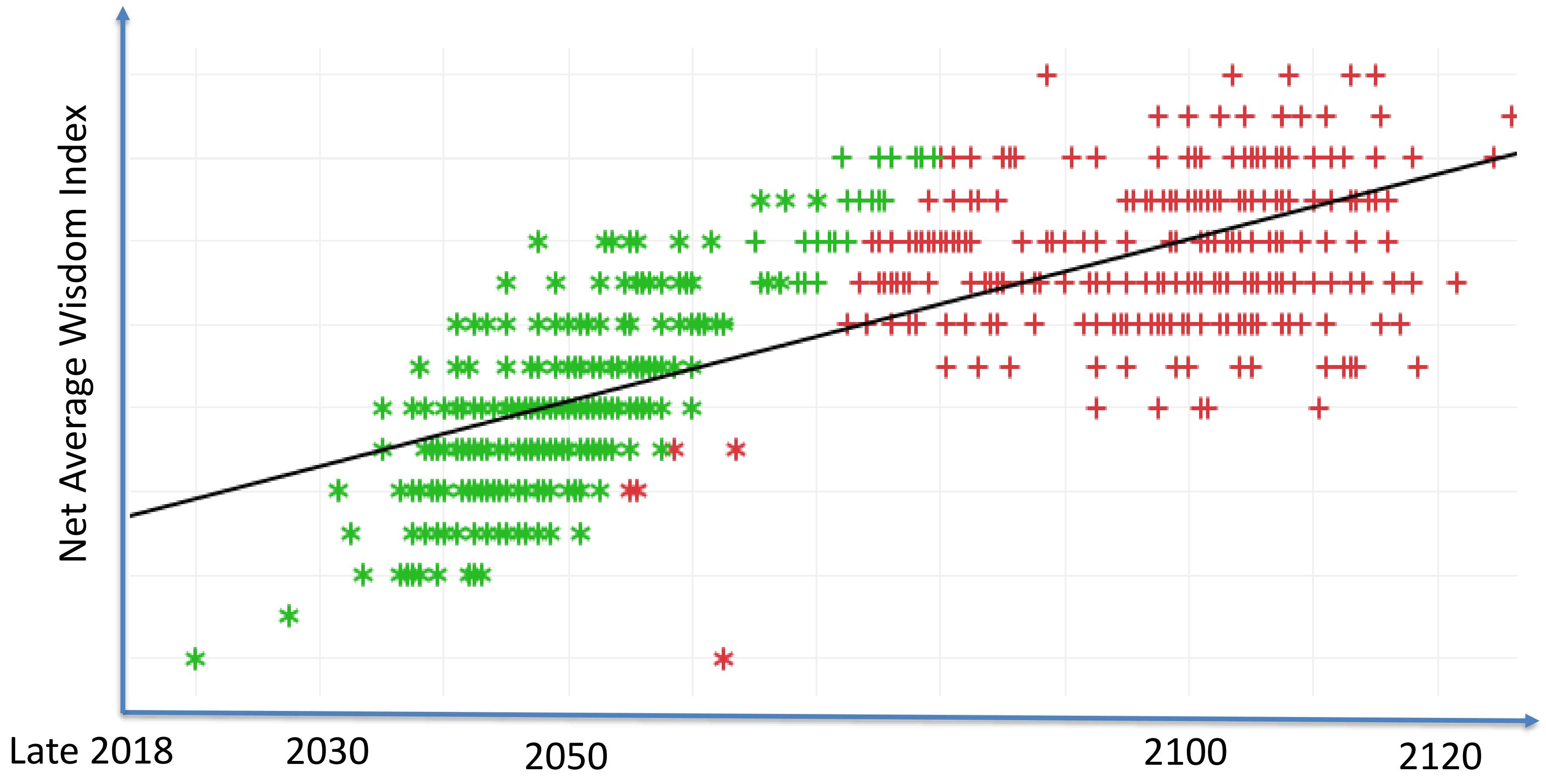


† Net Average Wisdom Index = TBD

‡ Data scattered to fit Blue line (See Appendix Black Box for methodology)

Wisdom Index revised (for revised humor)

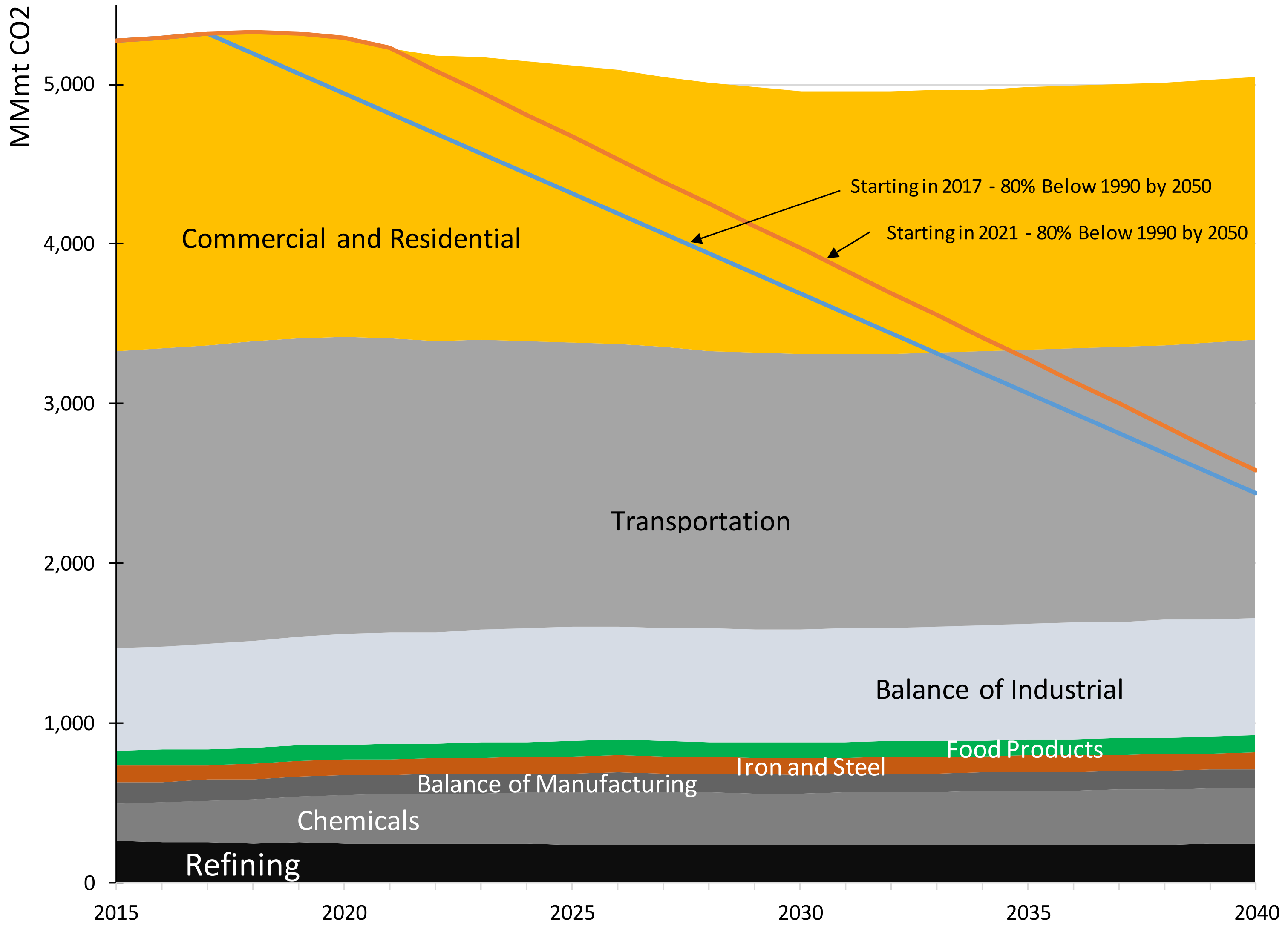
Human's Net Average Wisdom Index is inclining since November 12th 2018 ~ 9am (MST) † ‡



† Net Average Wisdom Index = Green and Red

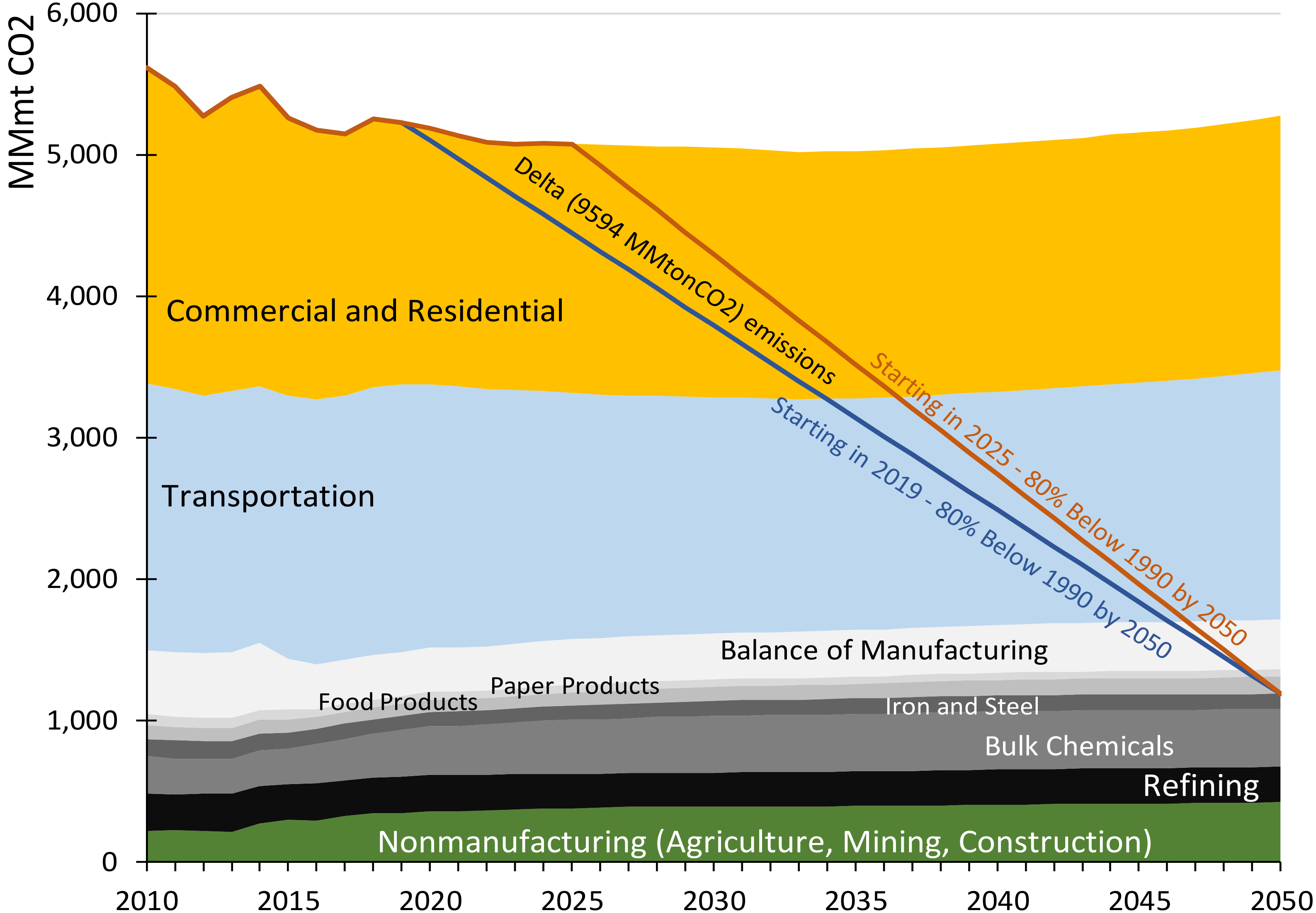
‡ Data scattered to fit Dark Gray line (See Appendix Black Box for methodology)

U.S. CO2 Emission Projections AEO 2016 RC



EIA Annual Energy Outlook 2016 Reference Case (http://www.eia.gov/forecasts/aeo/)

U.S. CO2 Emission Projections AEO 2018 RC

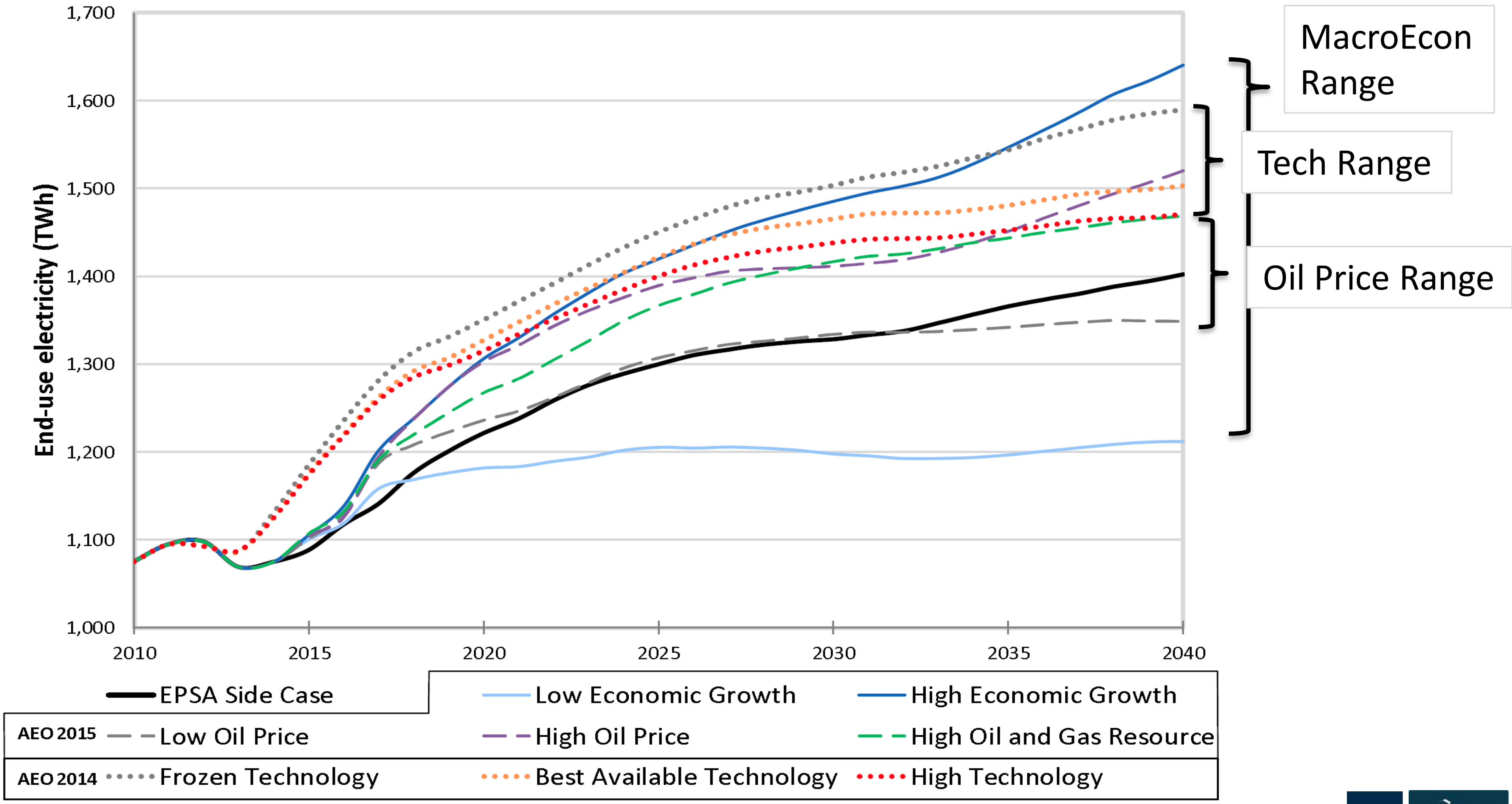


EIA Annual Energy Outlook 2018 Reference Case (http://www.eia.gov/forecasts/aeo/)

NEMS: Annual Energy Outlook

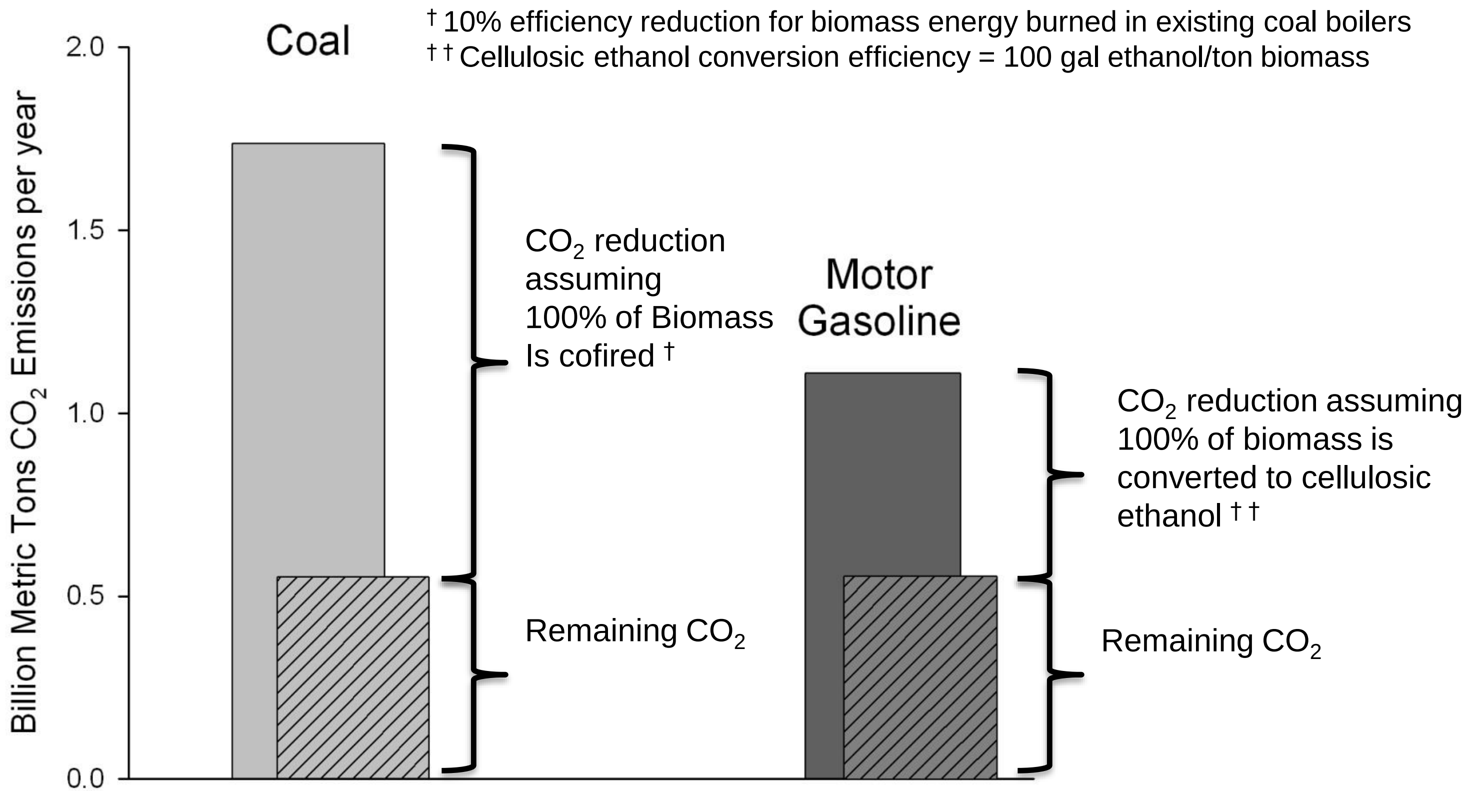
Macroeconomic assumption is the most significant

Aggregate industrial electricity consumption forecasts (9 AEO side cases) †



† DOE, U. S. (2017). Baseline Report: Electricity End Uses, Energy Efficiency, and Distributed Energy Resources Baseline. Quadrennial Energy Review Second Installment: Transforming the Nation's Electricity System. (QER 1.2) Washington D.C., U.S. Department of Energy.

1 billion tons of biomass Effect on 2009 CO_2 emissions

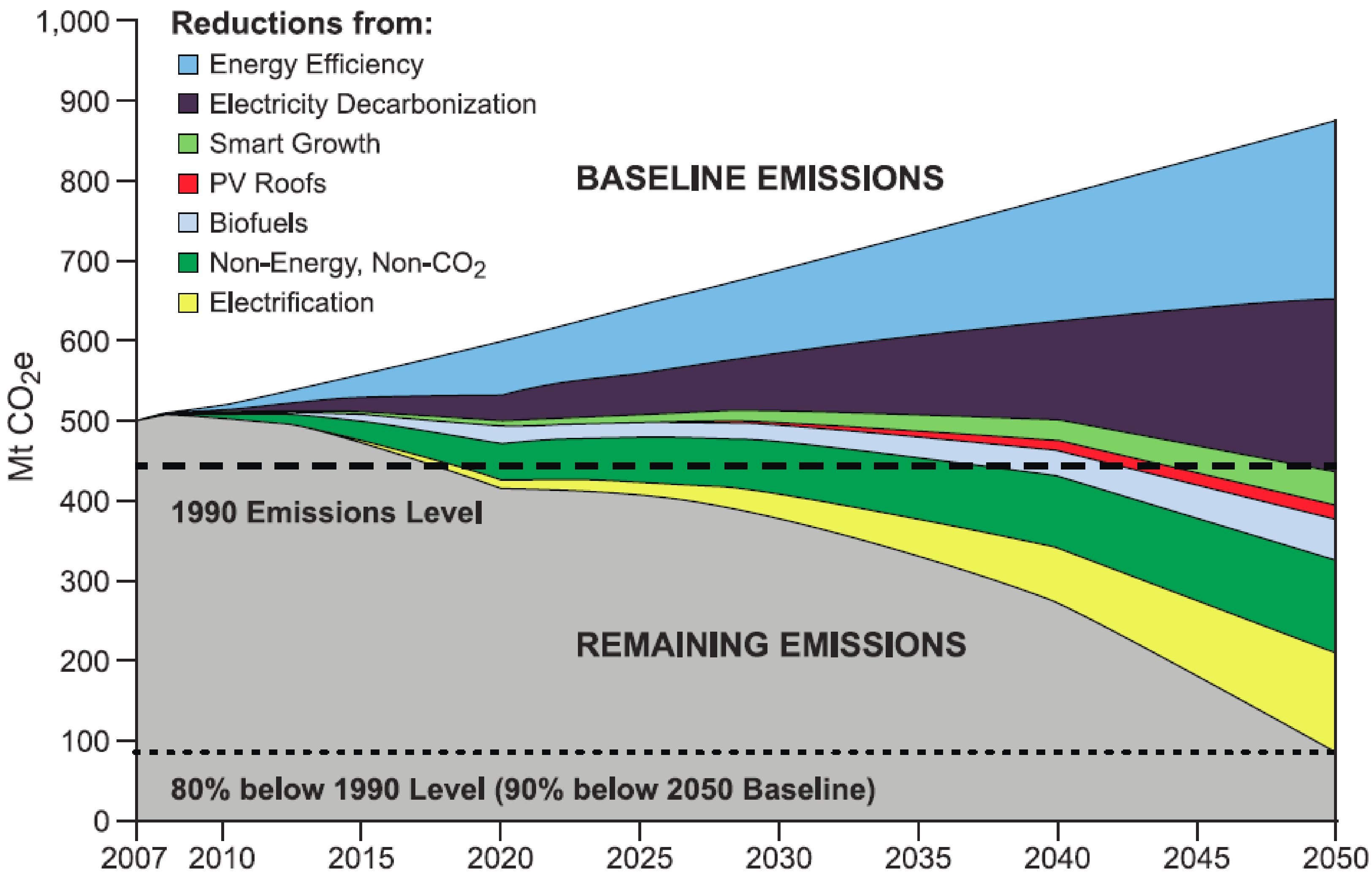


Biomass Allocation Model - Comparing Alternative Uses of Scarce Biomass Energy Resources through Estimations of Future Biomass Use for Liquid Fuels and Electricity

Developed at the National Energy Technology Laboratory (NETL) & Carnegie Mellon University, Pittsburgh, PA between 2006-2007

Meeting California’s Long-term Greenhouse Gas Reduction Goals

Williams, et al. (2012). "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity." Science **335**(6064): 53-59.



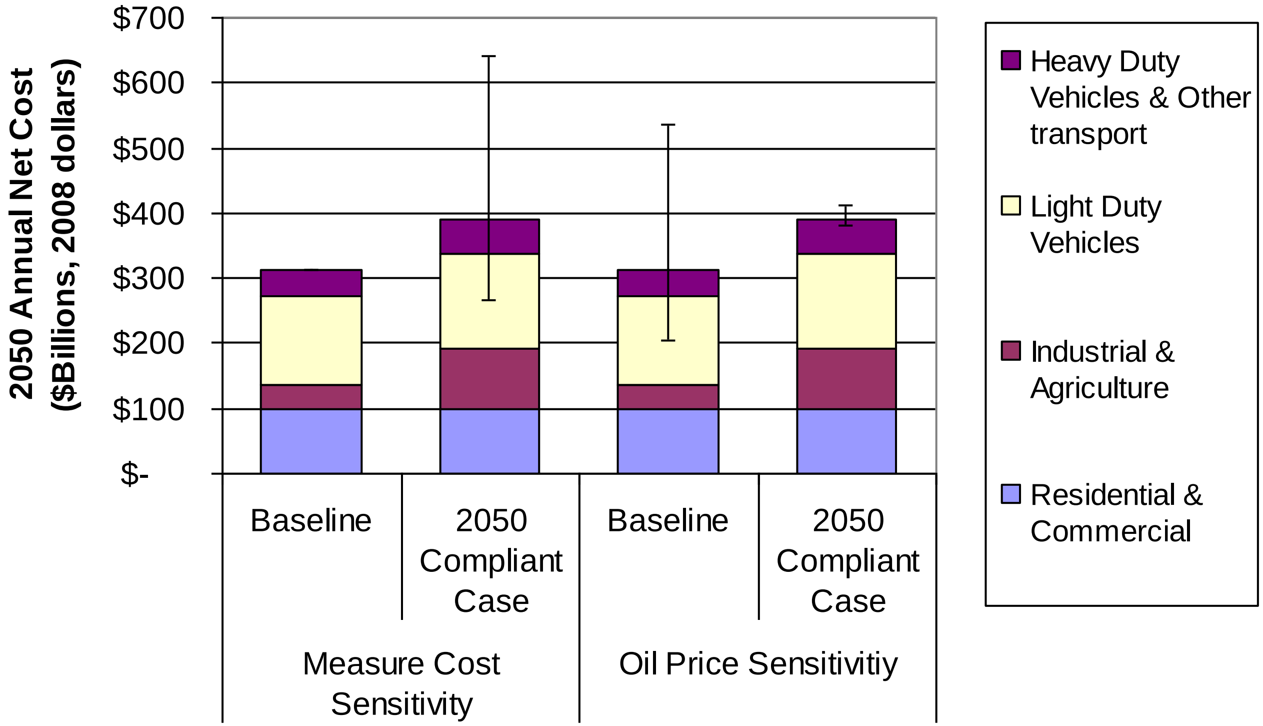
Reductions from:
Energy Efficiency
Electricity Decarbonization
Smart Growth
PV Roofs
Biofuels
Non-Energy, Non-CO_2
Electrification
BASELINE EMISSIONS
1990 Emissions Level
REMAINING EMISSIONS
80% below 1990 Level (90% below 2050 Baseline)
Mt CO_2e
1,000
900
800
700
600
500
400
300
200
100
0
2007
2010
2015
2020
2025
2030
2035
2040
2045
2050

Five Keys to Achieving 2050 Goal

1. Conservation
   - "Smart growth" - homes are closer to jobs & people drive less
2. Energy efficiency & on-site generation
   - Efficiency increases the feasibility of meeting electricity and fuel demands with low-carbon energy
   - Efficiency is essential to keep costs from prohibitive levels
3. Electrification & low-carbon generation
   - All 2050 compliant scenarios require high electrification using low-carbon generation sources
4. Low-carbon bio-fuels
   - Biofuels become a premium fuel for those uses that are not readily electrifiable, particularly Heavy Duty Vehicles
5. Mitigation of non-fuel use GHGs (methane, refrigerant gases, etc.)

"Believability" Example: Cost Sensitivity

- Measure costs in the 2050 Compliant Case are very uncertain: tested from 0.5x to 2x
- Oil prices are key driver of cost in Baseline case: tested using low to high EIA forecasts
  - Reduced dependence on oil in the 2050 Compliant Case reduces exposure to oil price uncertainty



Autonomous Vehicle Scenarios

Key factors influencing autonomous vehicles' energy and environmental outcome

William R. Morrow, I., J. B. Greenblatt, et al. (2014). Road Vehicle Automation - Lecture Notes in Mobility. G. Meyer and S. Beiker, Springer International Publishing: 127-135.

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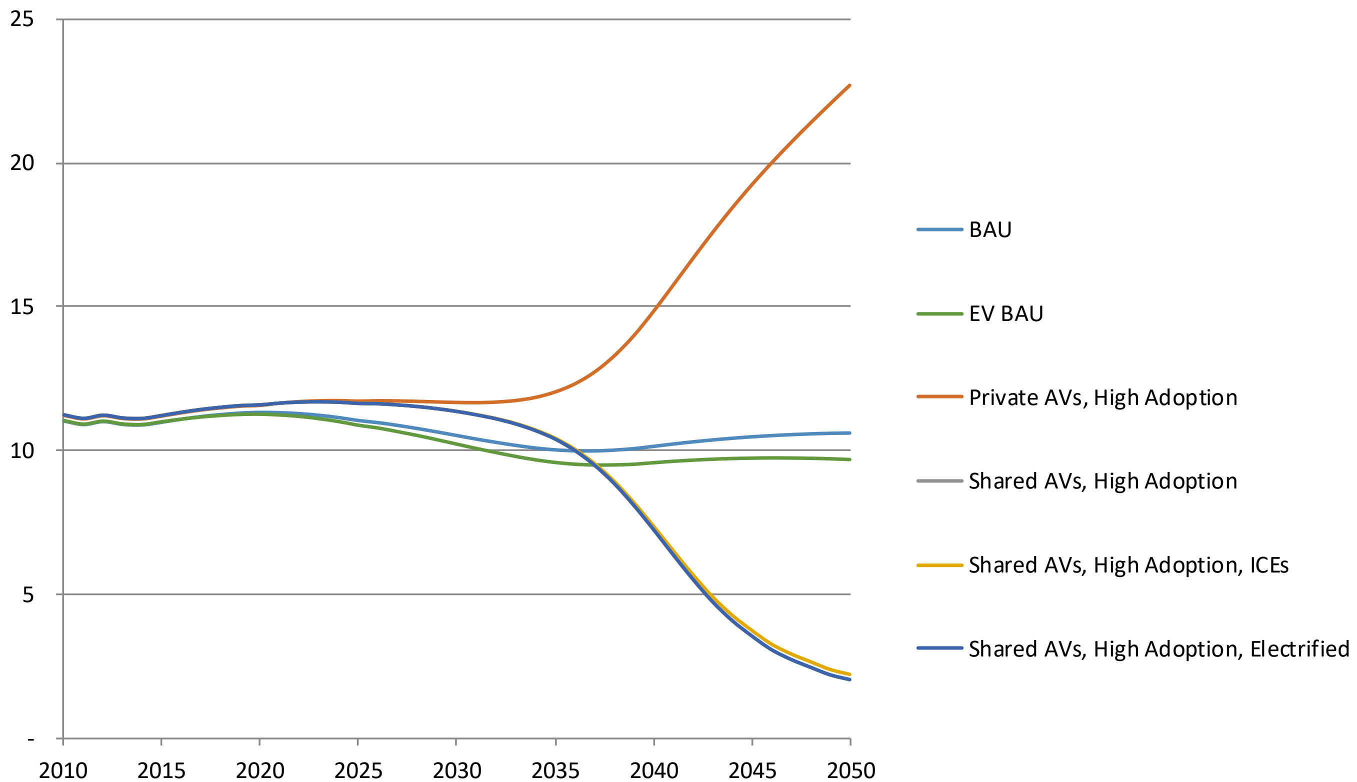
Prepared for:

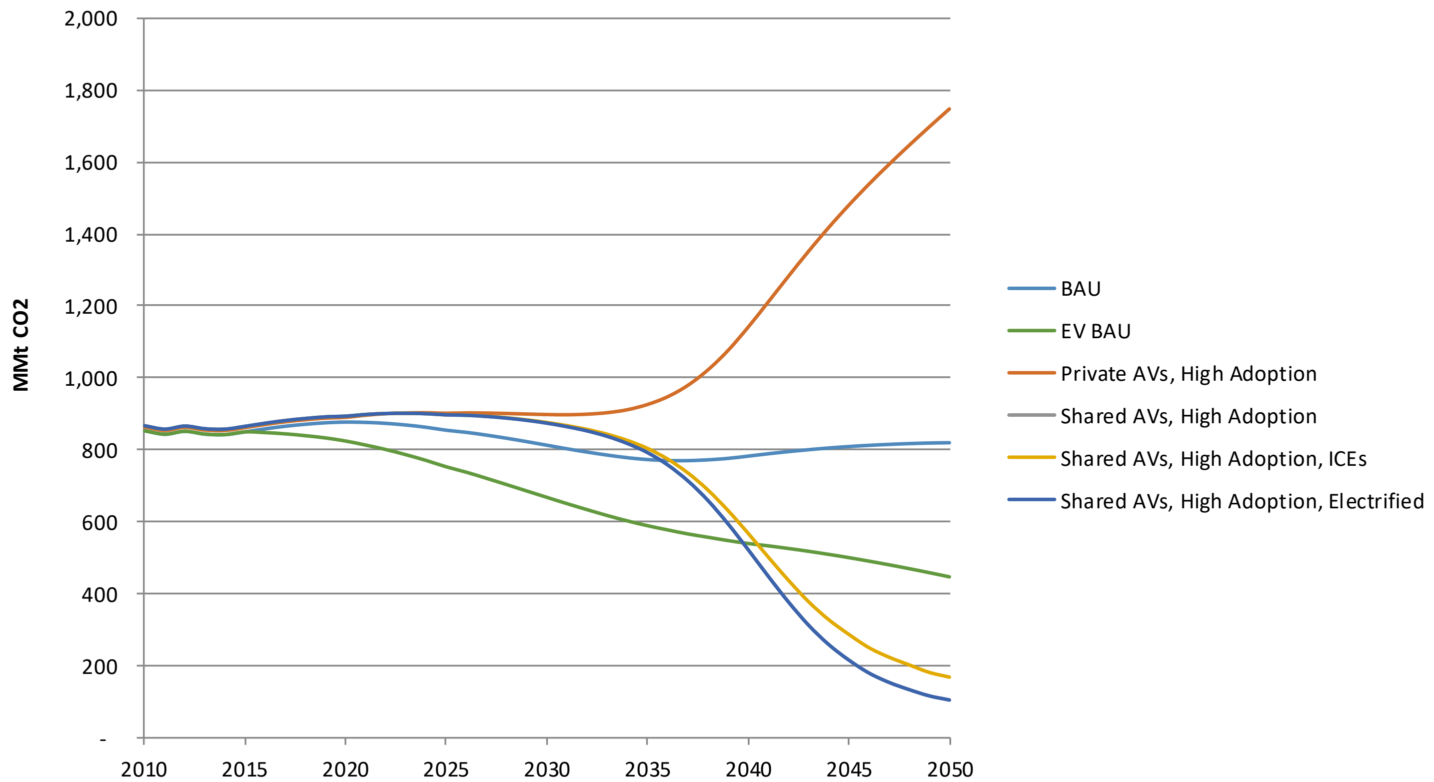
Key factors influencing autonomous vehicles' energy and environmental outcome

William R. Morrow, I., J. B. Greenblatt, et al. (2014). Road Vehicle Automation - Lecture Notes in Mobility. G. Meyer and S. Beiker, Springer International Publishing: 127-135.

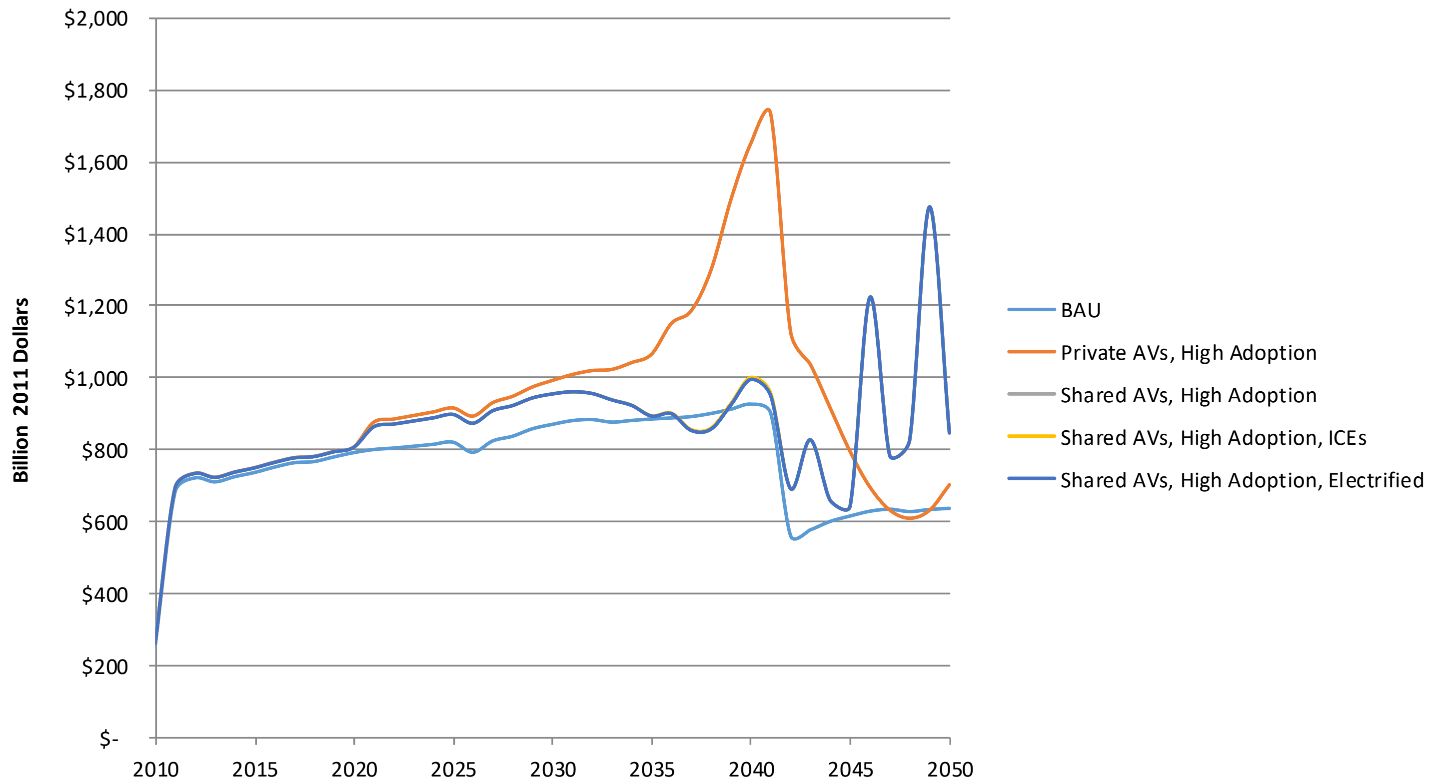
LDV Total Primary Energy (Quads)



Total CO_2 emissions
(from Gasoline consumption and Electricity production)



Cost – Combined vehicle capital and fuel variable costs



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U.S. DEPARTMENT OF ENERGY

Thank you

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