McCormick

Northwestern Engineering

Accelerating the development and deployment of clean technologies through prospective life-cycle systems analysis

Eric Masanet

Morris E. Fine Junior Professor of Materials and Manufacturing
Associate Professor of Mechanical Engineering
Associate Professor of Chemical and Biological Engineering
Guest Faculty Researcher, Argonne National Laboratory
eric.masanet@northwestern.edu

ERSAL

http://ersal.mccormick.northwestern.edu/

McCormick

Northwestern Engineering

Energy and Resource Systems Analysis Laboratory

- ERSAL develops mathematical models and decision support tools to ***quantify opportunities for reducing energy and resource use*** in:
  - Manufacturing processes and supply chains;
  - Product and material life-cycle systems; and
  - Information technology systems.

ERSAL

http://ersal.mccormick.northwestern.edu

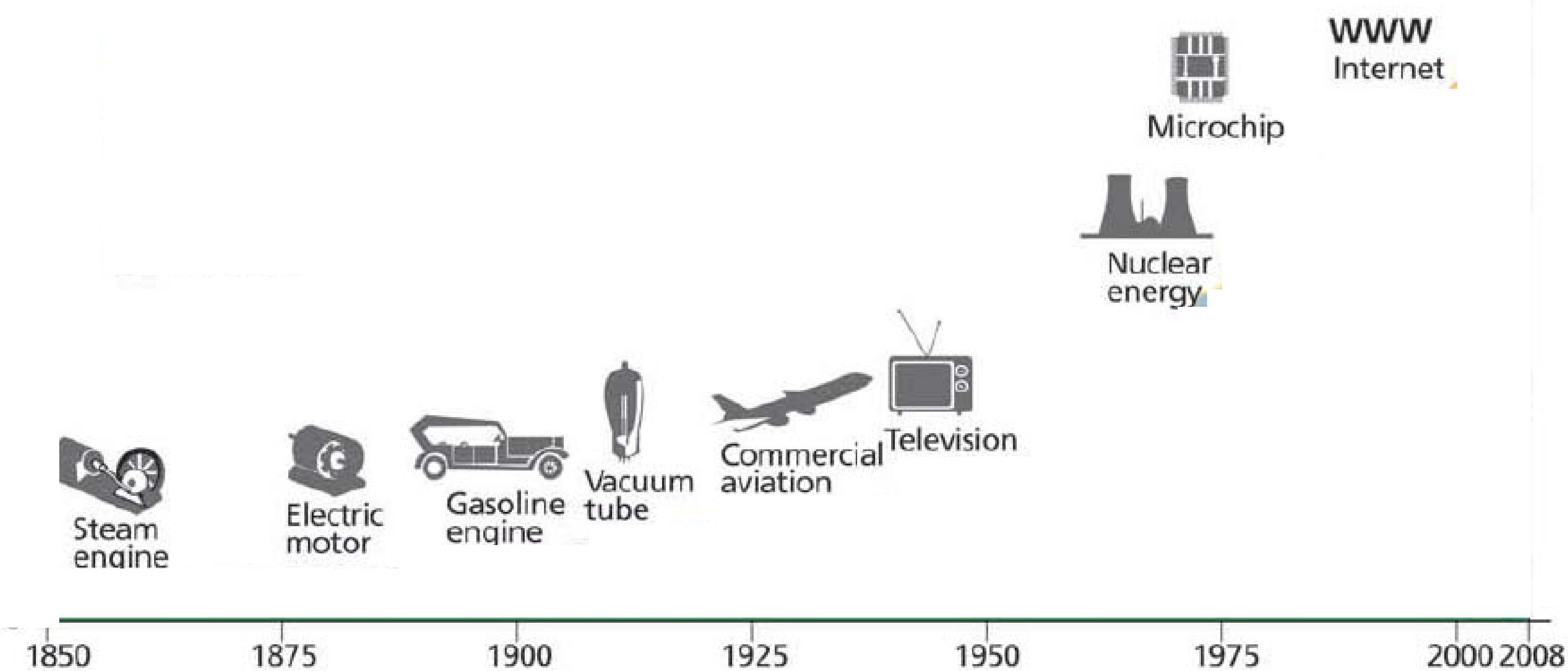
- Goal: Enable manufacturers and policy makers to identify ***robust*** technological, behavioral, and policy pathways toward more sustainable products and processes.

- Some current projects:
  - Supply chain environmental optimization (*National Science Foundation*)
  - Industrial cap and trade policy analysis (*California Air Resources Board*)
  - Geo-temporal energy analysis of cloud computing (*Google*)
  - Industrial energy and water efficient technology characterization (U.S. EPA)
  - Cost and environmental prioritization of advanced manufacturing technologies (*U.S. Department of Energy*)

McCormick

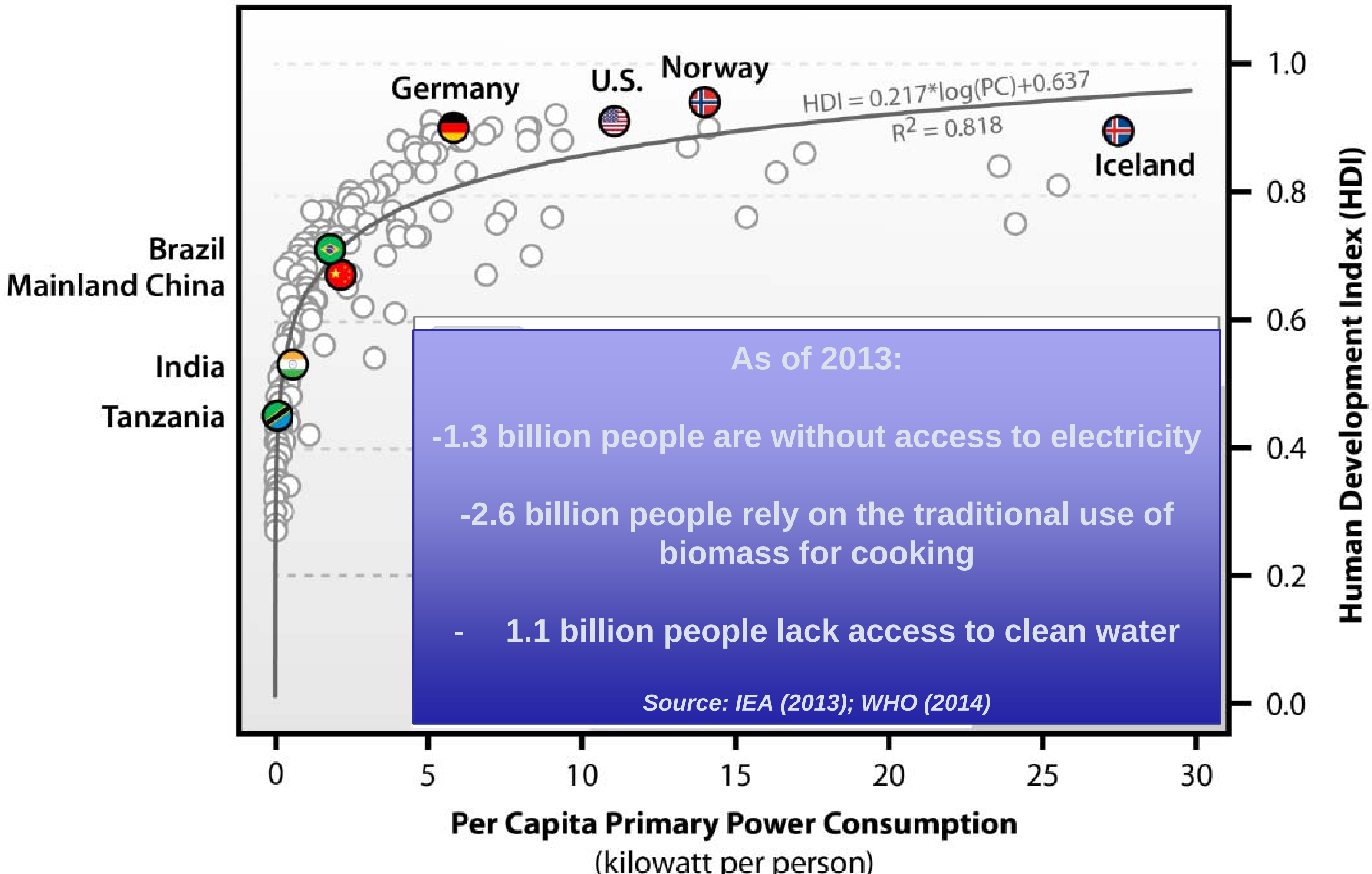
Northwestern Engineering

150 Years of Engineering Impact



Source: IIASA (2012). GEA.

Energy use and human development



As of 2013:

-1.3 billion people are without access to electricity

-2.6 billion people rely on the traditional use of biomass for cooking

- 1.1 billion people lack access to clean water

Source: IEA (2013); WHO (2014)

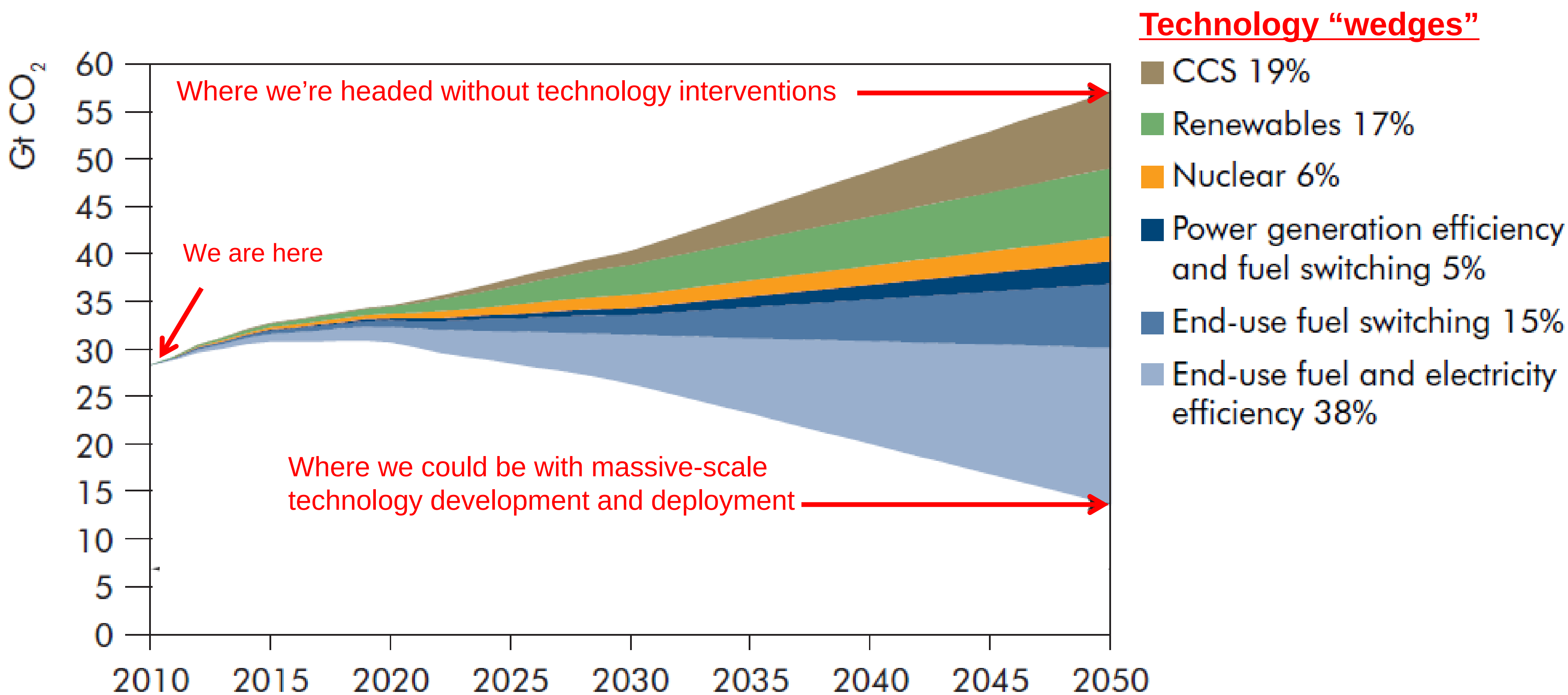
Source: Bruce E. Dale, Michigan State (IEA data)

McCormick

Northwestern Engineering

Engineering's Grand Challenge for the 21st Century:

Accelerating development and deployment of sustainable technologies



Source: International Energy Agency (IEA) (2010)

Notes: WEO = IEA World Energy Outlook; ETP = EA Energy Technology Perspectives

Manufacturing is vital to the U.S. economy

- 11% of U.S. GDP
- 12 million U.S. jobs
- 60% of U.S. engineering and science jobs
- 57% of U.S. Exports
- Nearly 20% of the worlds manufactured value added

Courtesy of Joe Cresko, AMO

Advanced Manufacturing Office – Goals and National Importance

The Advanced Manufacturing Partnership

Spark a renaissance in American manufacturing through public private partnerships that help our manufacturers compete with anyone in the world.

Office of Energy Efficiency and Renewable Energy

U.S. Dept. of Energy

Strengthen America's energy security, environmental quality, and economic vitality through **enhanced energy efficiency and productivity**

Advanced Manufacturing Office

Partner with industry, small business, universities, and other stakeholders to invest in technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

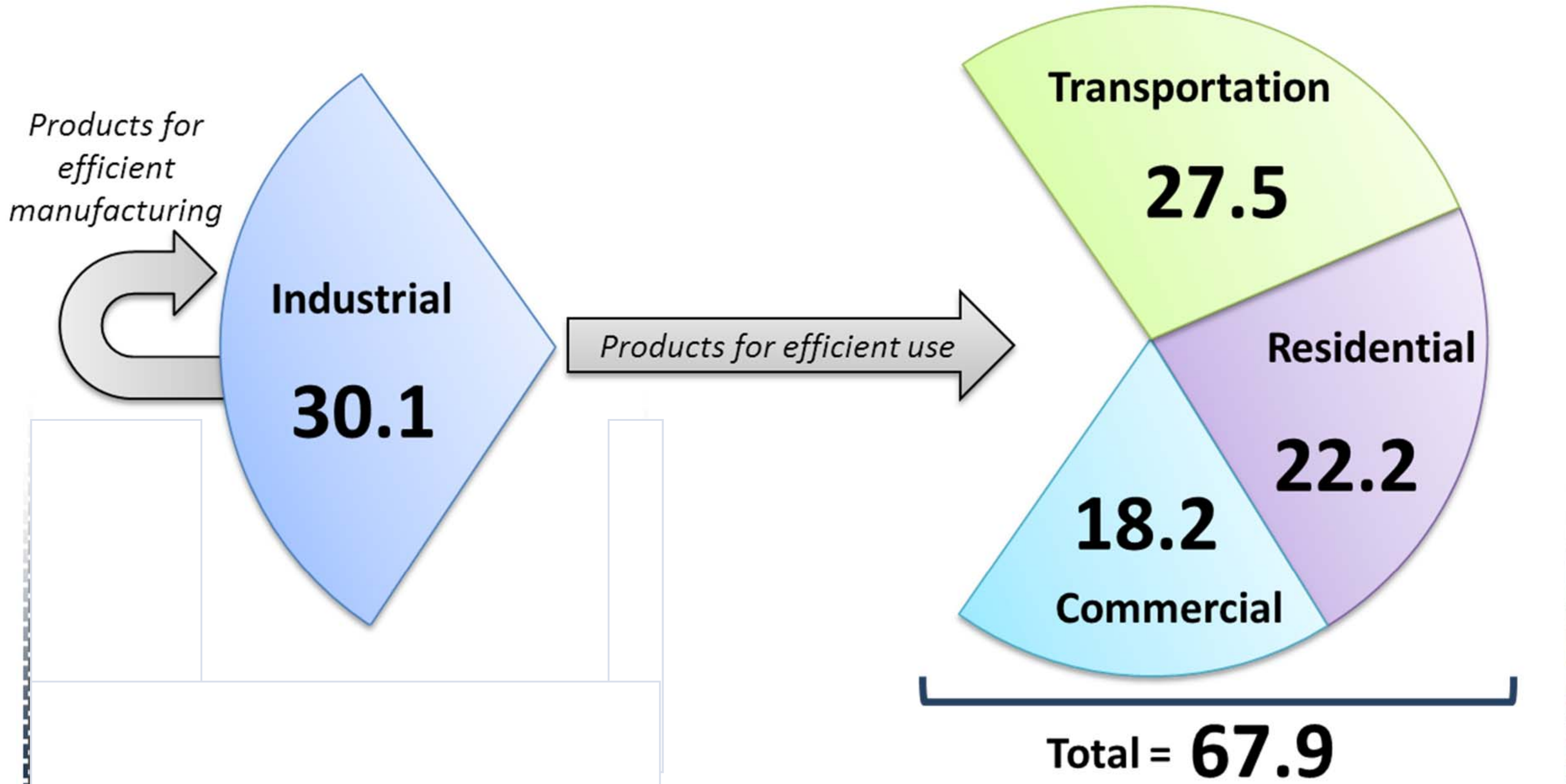
Courtesy of Joe Cresko, AMO

McCormick

Northwestern Engineering

Energy Economy-wide lifecycle impacts

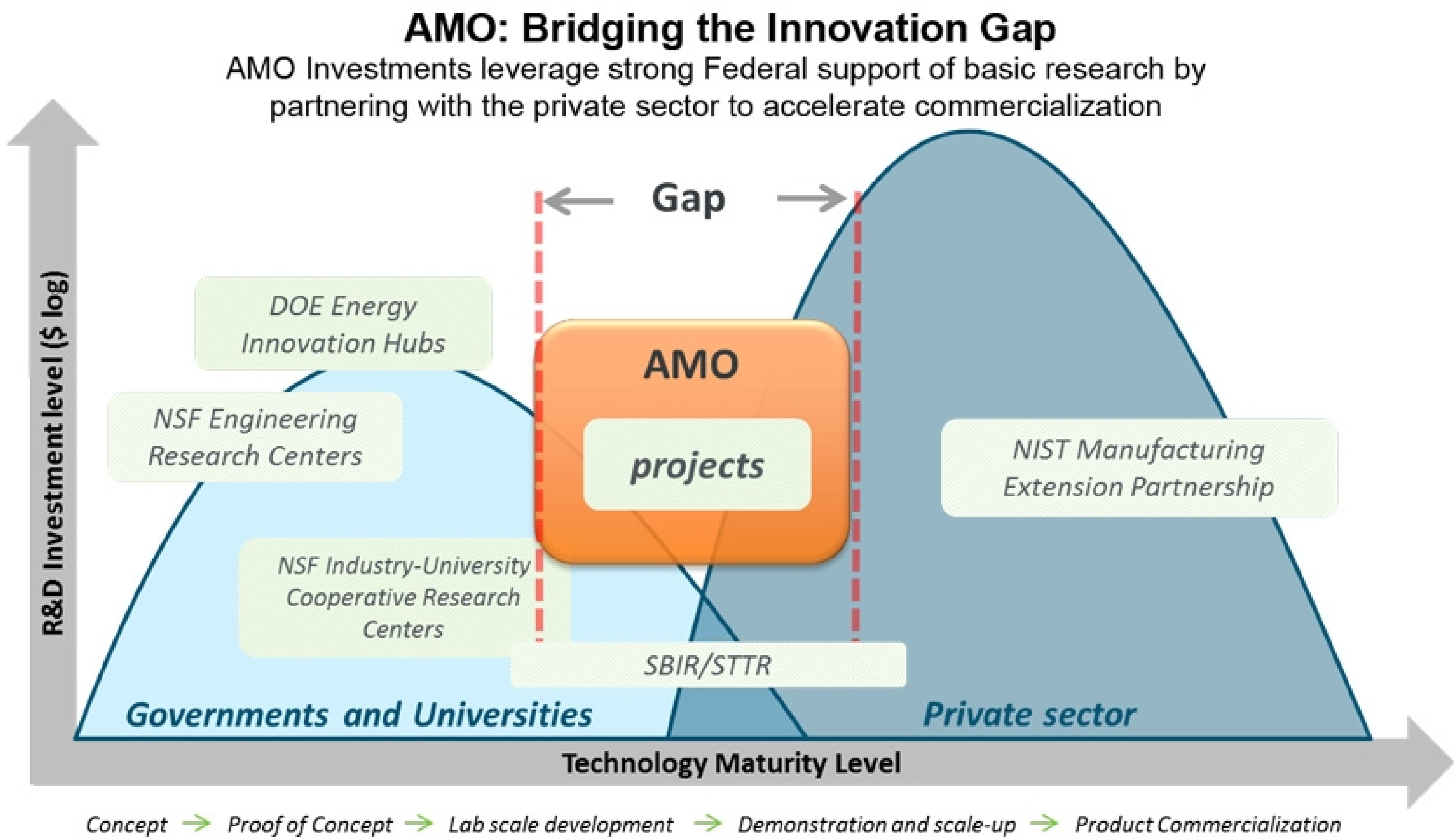
Primary Energy Consumption by Sector, 2010 (Quads)



Manufacturing investments impact all sectors

Courtesy of Joe Cresko, AMO

Research Motivations Part II: Transitioning to a Clean Manufacturing Economy

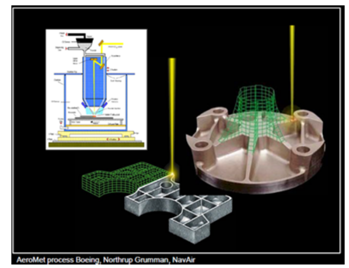


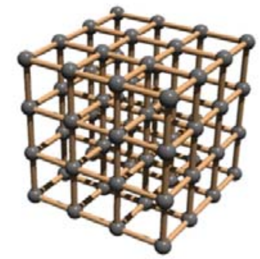
U.S. Department of Energy Advanced Manufacturing Office (AMO)

Accelerating technology development

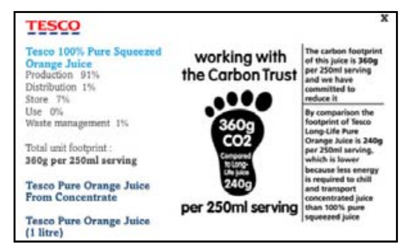
ERSAL research thrust:

- Prospective life-cycle systems analysis:
  - Enables robust engineering and policy decisions ***today*** to lead to greatest sustainability benefits ***tomorrow***
  - Development of large-scale spatio-temporal systems models:
    - Mathematical integration of physical, economic, policy, and environmental models and data
    - Functional relationships to engineering properties
    - Uncertainty and scenario capabilities for robust decisions
    - Enables high-reward investments through technology policy



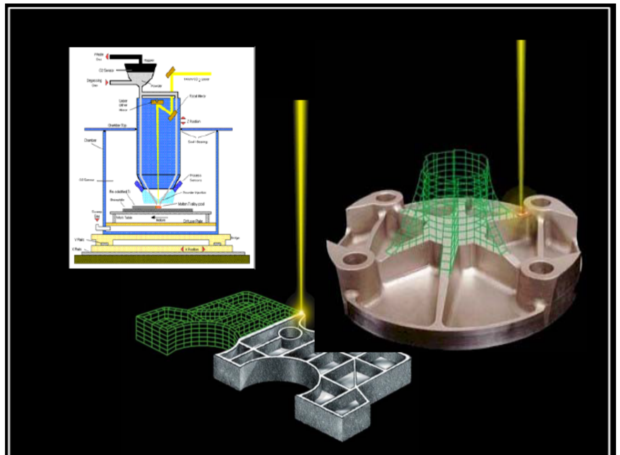


U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



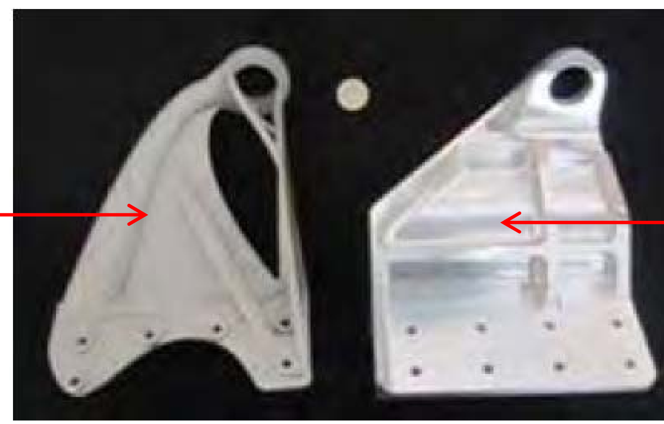
Additive Manufacturing Example

- 3-D graphical models, parts built in layers
- No tools, dies, or forms
- Near final shape
- Reduced delivery times 75%
- Mechanical properties equivalent to wrought
- Reduced material use
- Reduced inventory
- Significant cost and energy savings



AeroMet process Boeing, Northrup Grumman, NavAir

Airbus example (120 brackets)

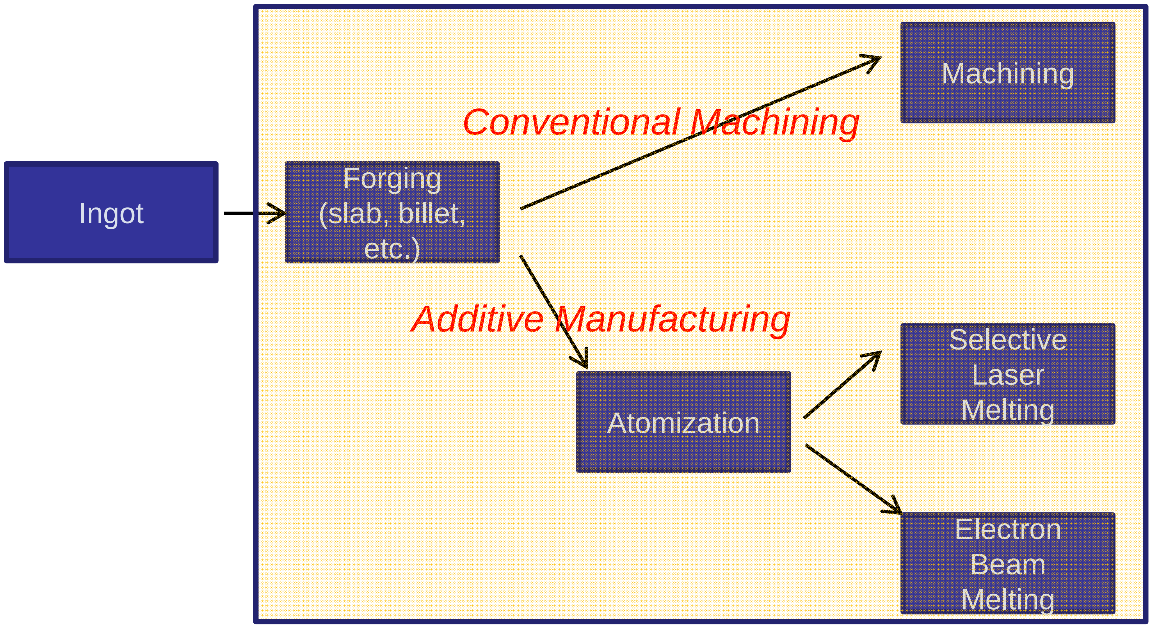


Additive Manufacturing

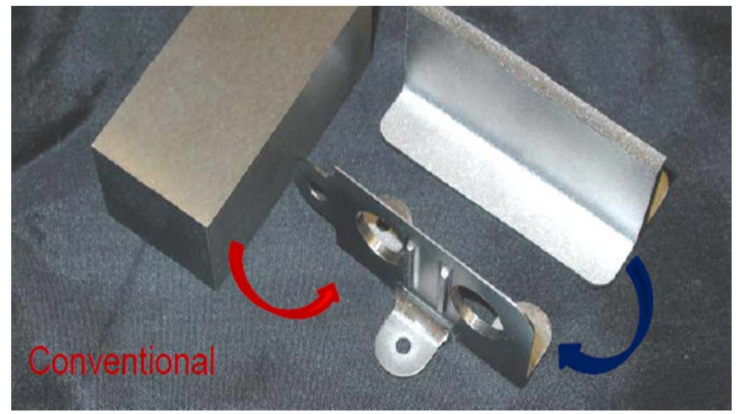
0.38 kg

Conventional Machining

1.09 kg



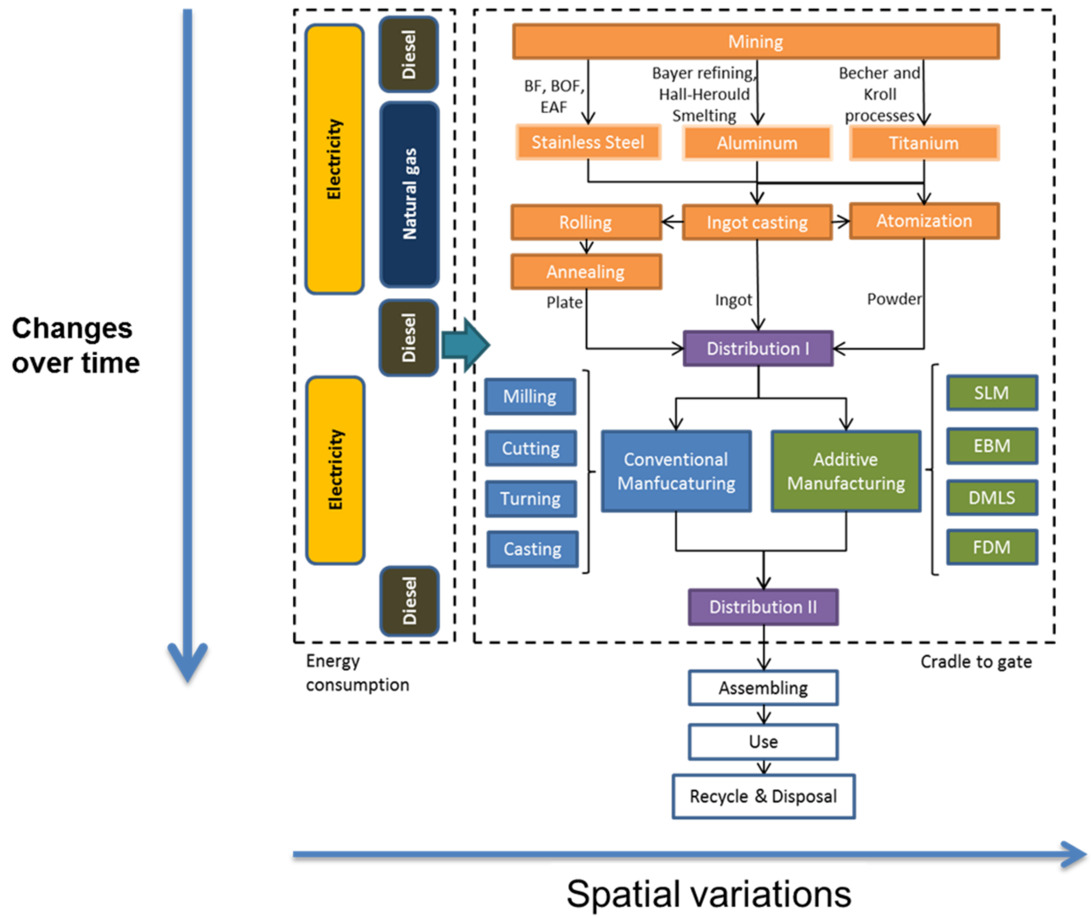
High embodied energy of ingot plus high buy-to-fly ratio of machining pathway drives energy differences



Process	Final part kg	Ingot consumed kg	Raw mat'l MJ	Manuf MJ	Transport MJ	Use phase MJ	End of life	Total energy per bracket MJ	Total energy per (120 brackets) MJ
Machining	1.09	9.69	8892	990	41	218,000	Not considered	227,923	27.4 MM
SLM	0.38	0.64	583	198	14	76,000	Not considered	76,795	9.2 MM
EBM	0.38	0.64	583	154	14	76,000	Not considered	76,751	9.2 MM

Courtesy of Josh Warren and Sujit Das, ORNL

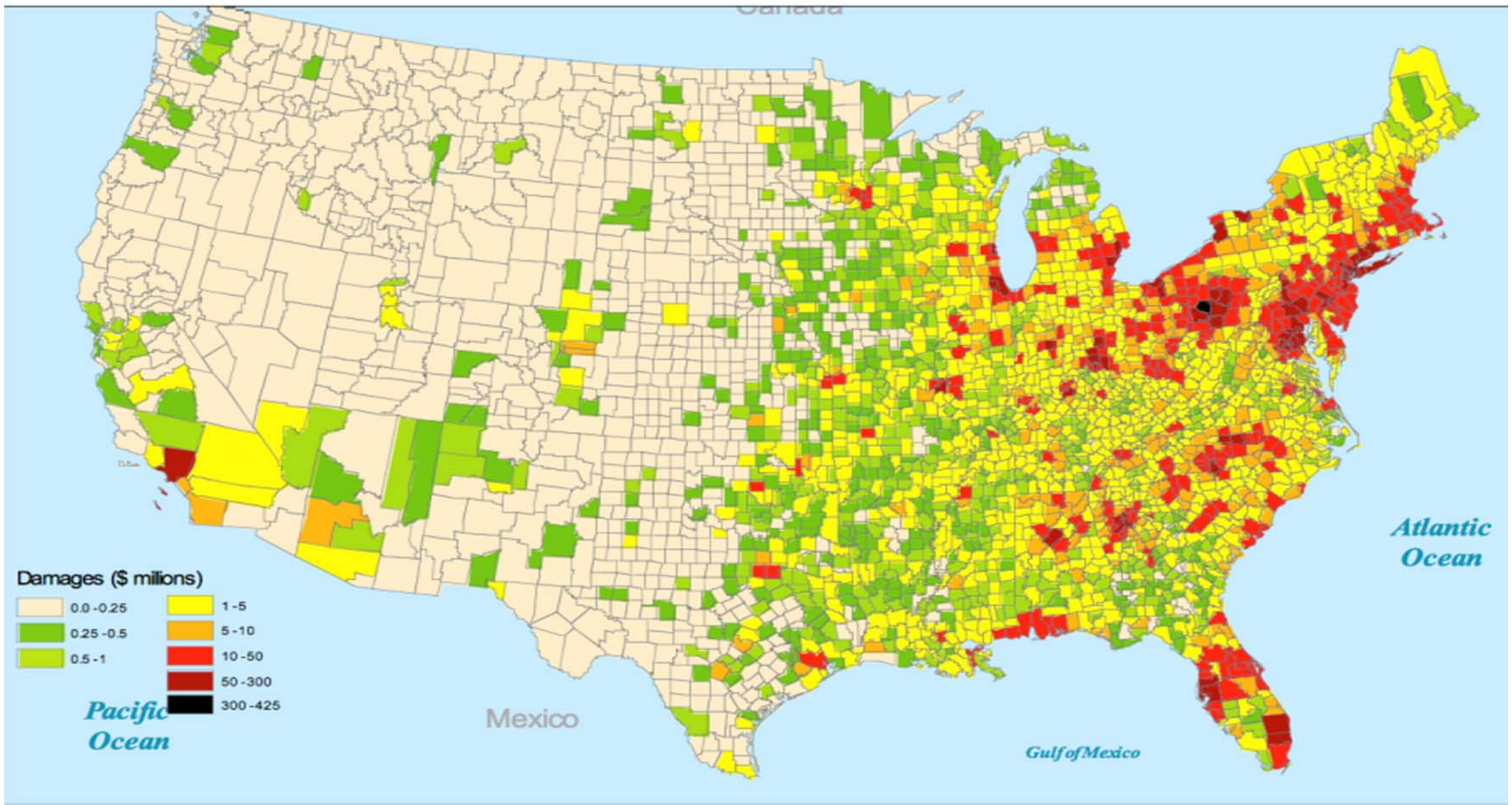
Spatial-temporal systems modeling framework



Huang, R., Riddle, M., Graziano, D., and E. Masanet (2014). "The Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft." Journal of Cleaner Production. Under review.

Why location matters

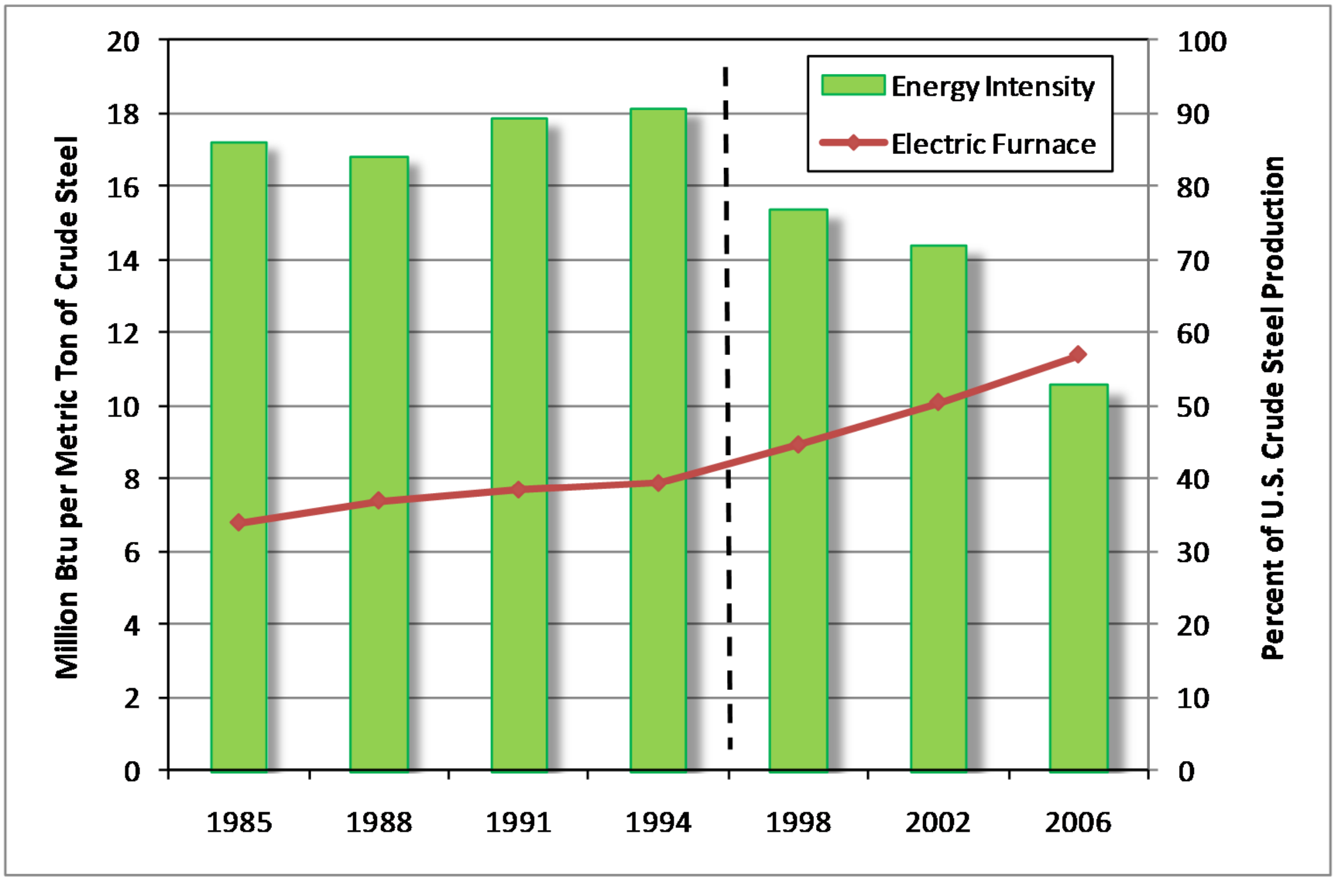
Monetized Health Damage from Fossil-fuel Electric Power Generators



Source: NRC (2010)

Why time matters

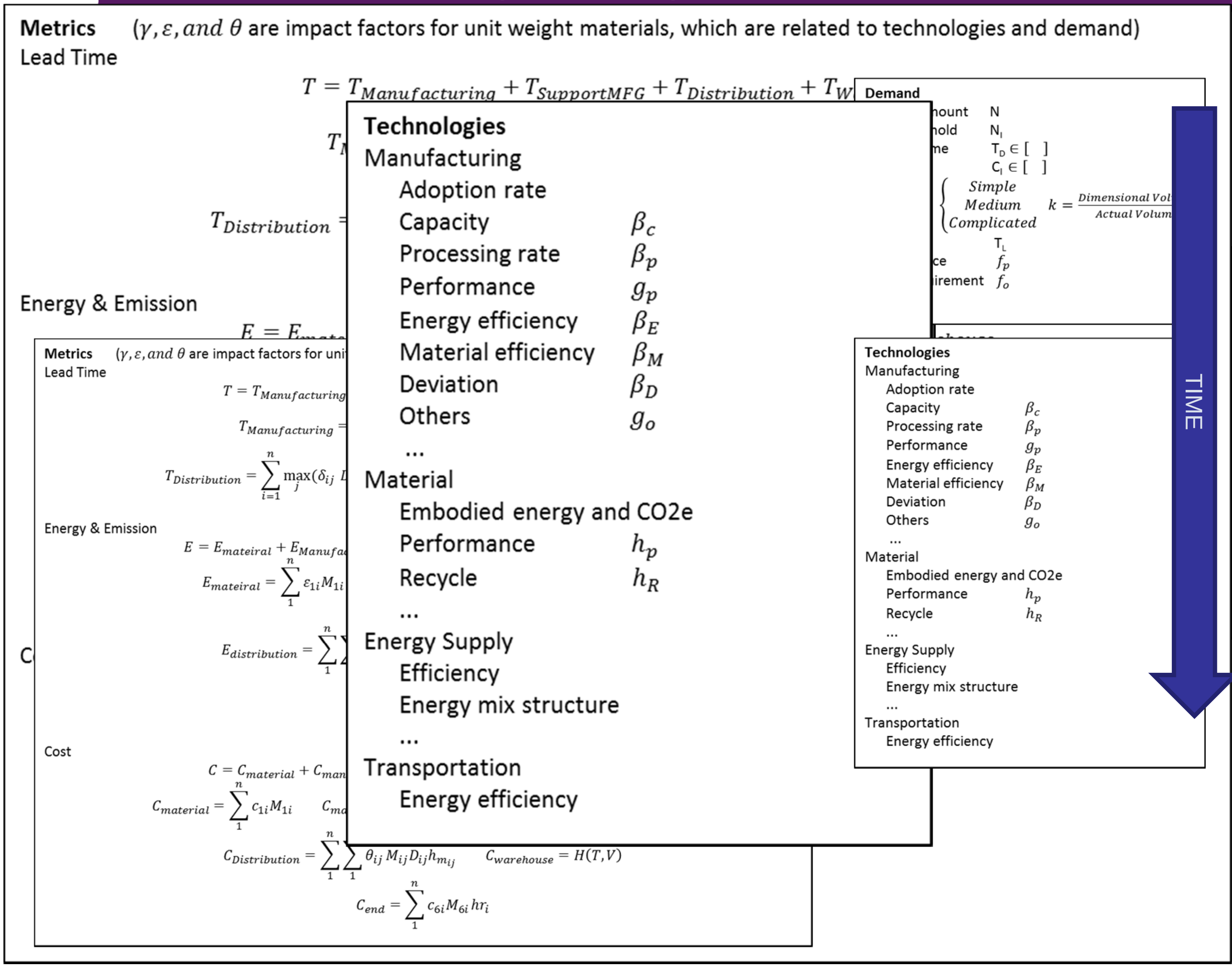
Energy intensity of U.S. steelmaking



Note: vertical dashed line indicates a change in the time period between data points
Sources: U.S. DOE (2010), USGS (2010b), World Steel (2010)

McCormick

Northwestern Engineering



U.S. Aircraft Fleet Case Study (2015-2050)

Huang, R., Riddle, M., Graziano, D., and E. Masanet (2014). "The Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft." Journal of Cleaner Production. Under review.

Replaceable mass screening

Table 2: Aircraft component system attribute ratings

Component systems	*Component category*	Mass fraction	Load rating	Shape complexity rating	Geometric volume rating	Feasibility evaluation score*
Wing systems		0.24				
	Structural	*0.95*	*High*	*Medium*	*High*	*4*
	Auxiliary	*0.05*	*High*	*Low*	*Low*	*5*
Body systems		**0.19**				
	Structural	*0.95*	*High*	*Medium*	*High*	*4*
	Auxiliary	***0.05***	***Medium***	***Low***	***Low***	***6***
Furnish & equip systems		**0.13**				
	Structural	***0.36***	***Low-Medium***	***Medium***	***Low-Medium***	***7***
	Functional	***0.57***	***Low***	***Medium***	***Medium***	***7***
	Auxiliary	***0.07***	***Low***	***Low***	***Low***	***7***
Engine		**0.12**				
	Structural	*0.17*	*High*	*Medium*	*High*	*4*
	Functional	***0.77***	***High***	***High***	***Medium-High***	***5.5***
	Auxiliary	***0.06***	***Medium-High***	***Low***	***Low***	***5.5***
Alighting gear systems		0.09				
	Structural	*0.95*	*High*	*Medium*	*High*	*4*
	Auxiliary	*0.05*	*High*	*Low*	*Low*	*5*
Tail systems		0.04				
	Structural	*0.95*	*High*	*Medium*	*High*	*4*
	Auxiliary	*0.05*	*High*	*Low*	*Low*	*5*
Propulsion systems		**0.04**				
	Functional	***1.00***	***High***	***High***	***Medium***	***6***
Nacelle systems		***0.04***				
	Structure	*0.95*	*High*	*Medium*	*High*	*4*
	Auxiliary	***0.05***	***Low-Medium***	***Low***	***Low***	***6.5***

** To determine feasibility scores, numerical values of 1, 2, and 3 were assigned to ratings of high, medium, and low, respectively, for load and geometric volume. Numerical values of 3, 2, and 1 were assigned to ratings of high, medium, and low, respectively, for shape complexity. Component categories with feasibility scores greater than 5 (bolded in this table) were deemed most likely for near-term adoption of AM components.*

Huang, R., Riddle, M., Graziano, D., and E. Masanet (2014). “The Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft.” Journal of Cleaner Production. Under review.

Replaceable mass and timing

Table 3: Replaceable mass by metal alloy, component system, and component category

Component system	Category	Replaceable mass in average aircraft (kg)* Al alloy	Ti alloy	Ni alloy	Steel
Body systems	Auxiliary	80-200			
Furnishings and equipment	Structural	70-130			
	Functional	1450-1930			
Engine	Functional		680-1350	940-1880	100-190
	Auxiliary		50-90	50-90	50-90
Propulsion systems	Functional		330-810		
Nacelle Systems	Auxiliary		20-40		
	Total	**1590-2260**	**1070-2290**	**980-1960**	**140-280**

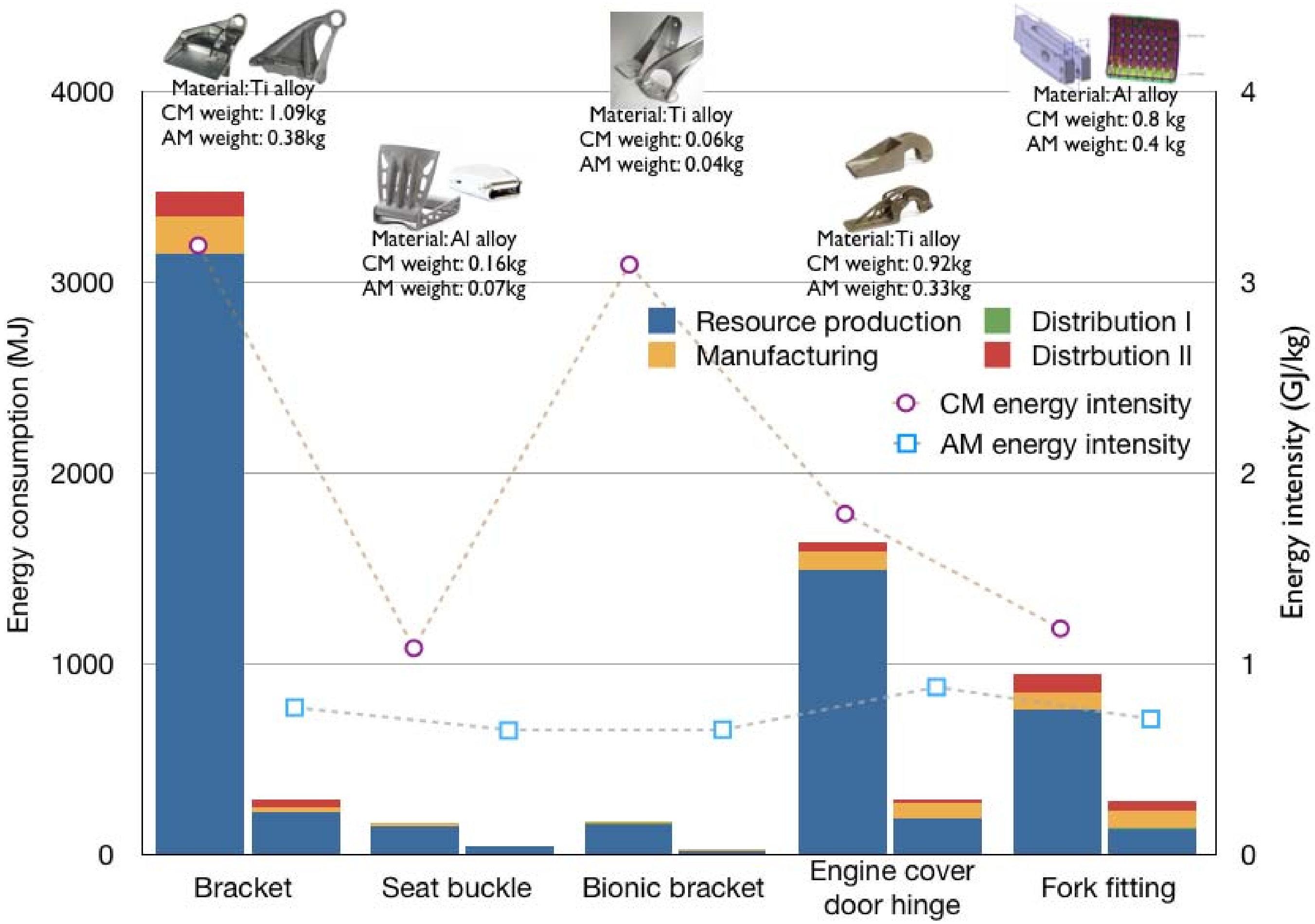
** Based on an average aircraft empty operating mass of 40,622 kg [43, 44]*

Table 8. Temporal availability assumptions

Component system	Component category	Availability
Body systems	Auxiliary	10 years (2024)
Furnishings and equipment systems	Structural	5-10 years* (2019-2024)
Furnishings and equipment systems	Functional	10 years (2024)
Engine	Functional	20 years (2034)
Engine	Auxiliary	10 years (2024)
Propulsion systems	Functional	20 years (2034)
Nacelle systems	Auxiliary	5 years (2019)

**5 years for galley and lavatory, 10 years for floor panel, fasteners and other*

Component level results



Temporal fleet adoption modeling

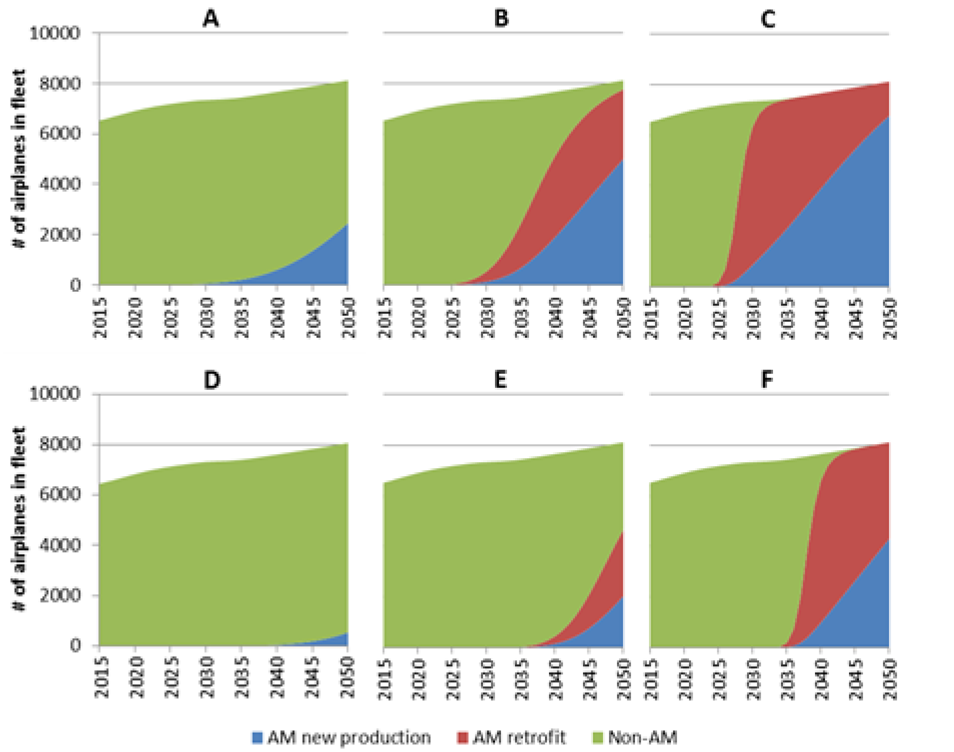
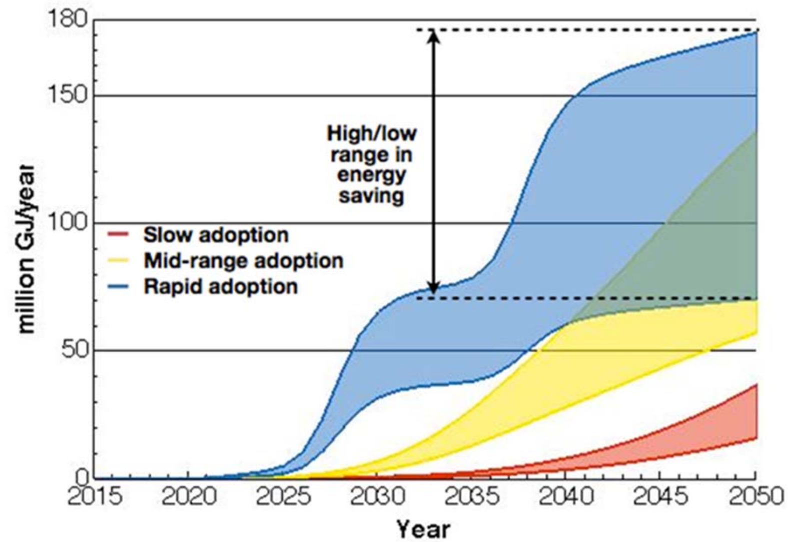


Figure 3: Incorporation of AM components into fleet of aircraft: (A) furnishings and equipment systems, slow adoption; (B) furnishings and equipment systems, mid-range adoption; (C) furnishings and equipment systems, rapid adoption; (D) engine, slow adoption; (E) engine, mid-range adoption; (F) engine, rapid adoption.



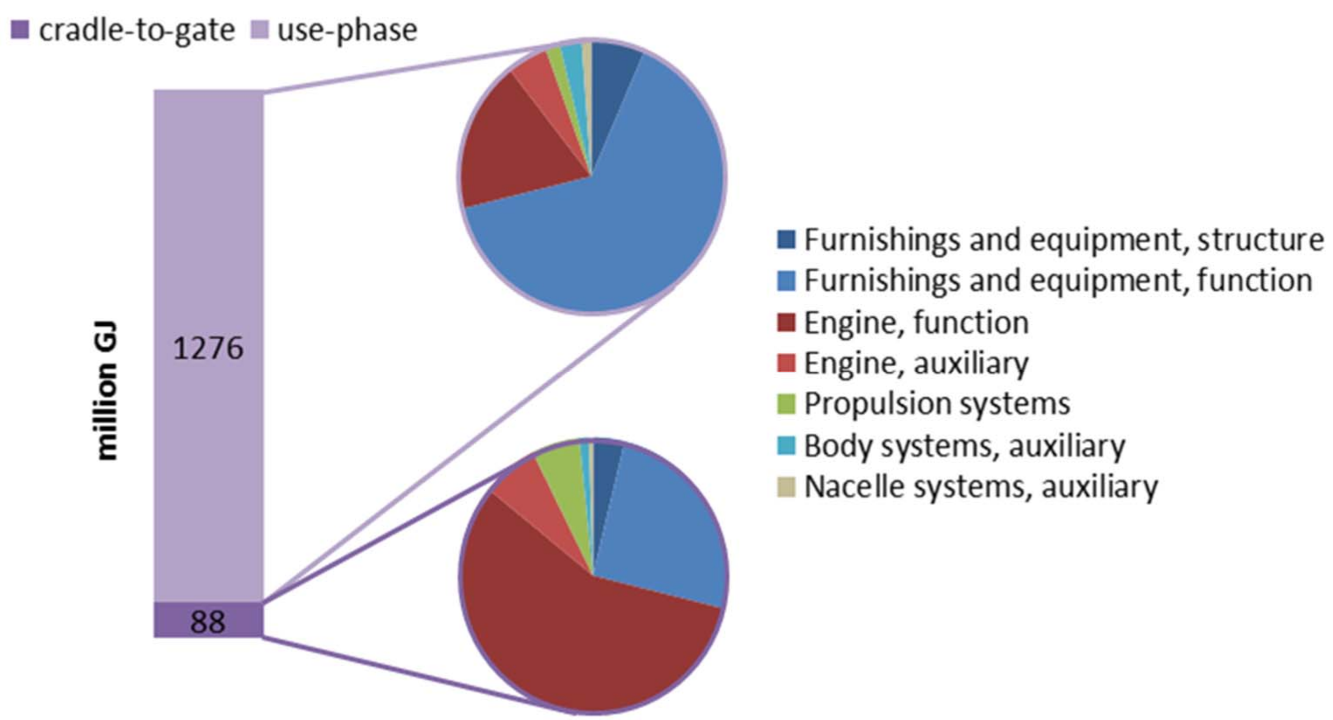
Policy and R&D levers for rapid adoption:

- Improved surface finish (basic research)
- Reduced residual stresses (basic research)
- Pilots and technology transfer
- Cost and externality incentives for AM adoption

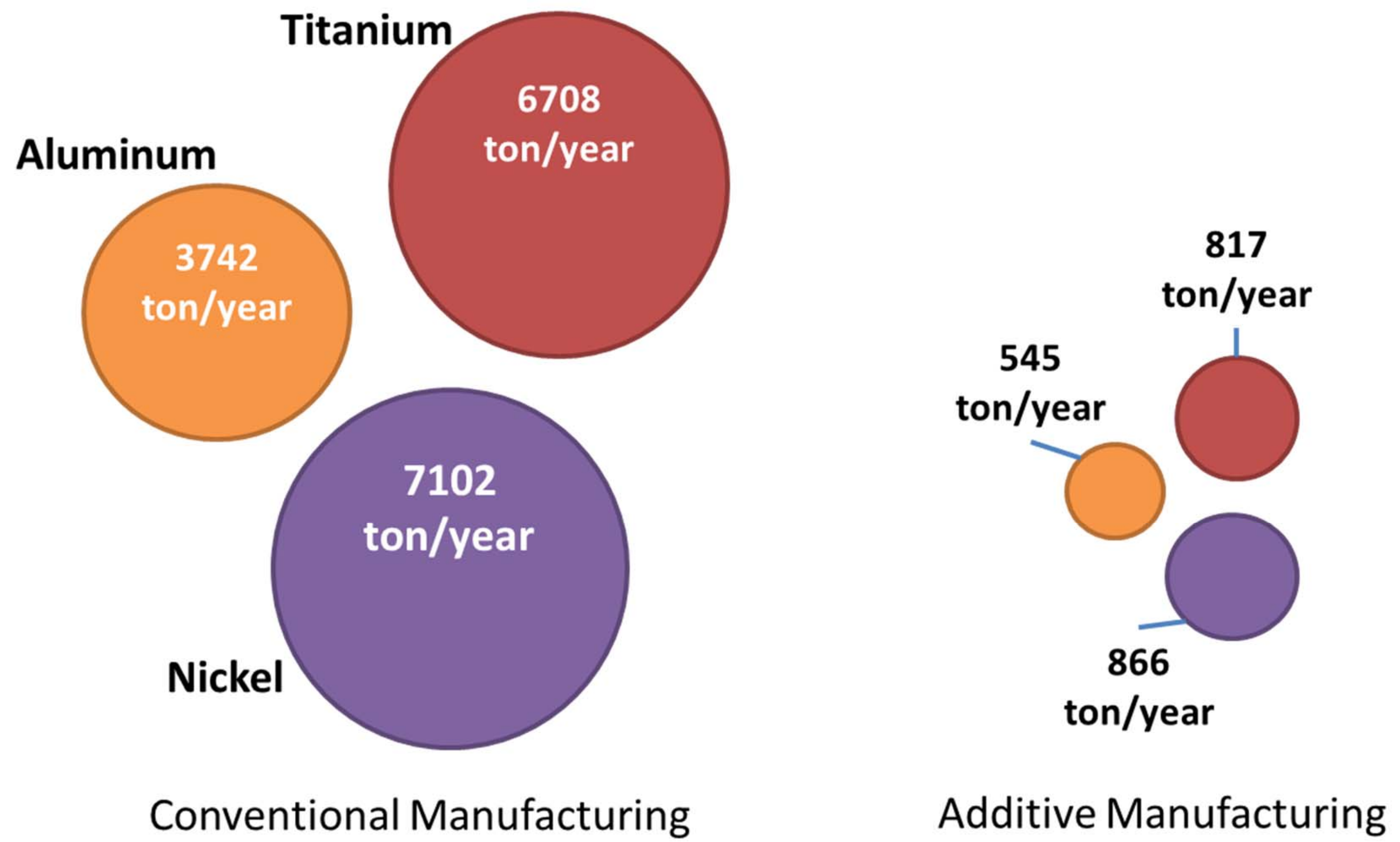
McCormick

Northwestern Engineering

Engineering functionality drives energy savings!



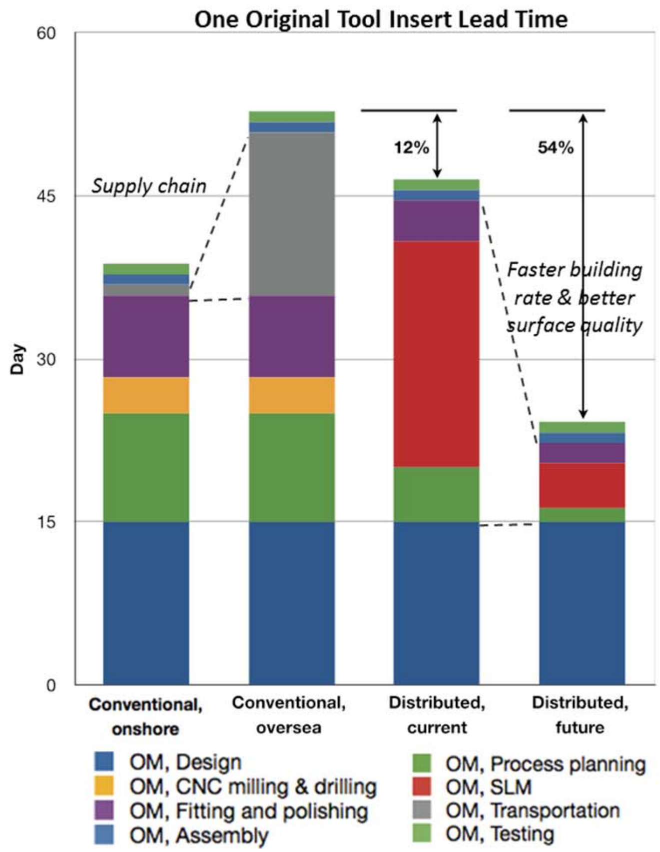
Raw materials requirements for replaceable components in 2050



Huang, R., Riddle, M., Graziano, D., and E. Masanet (2014). “The Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft.” Journal of Cleaner Production. Under review.

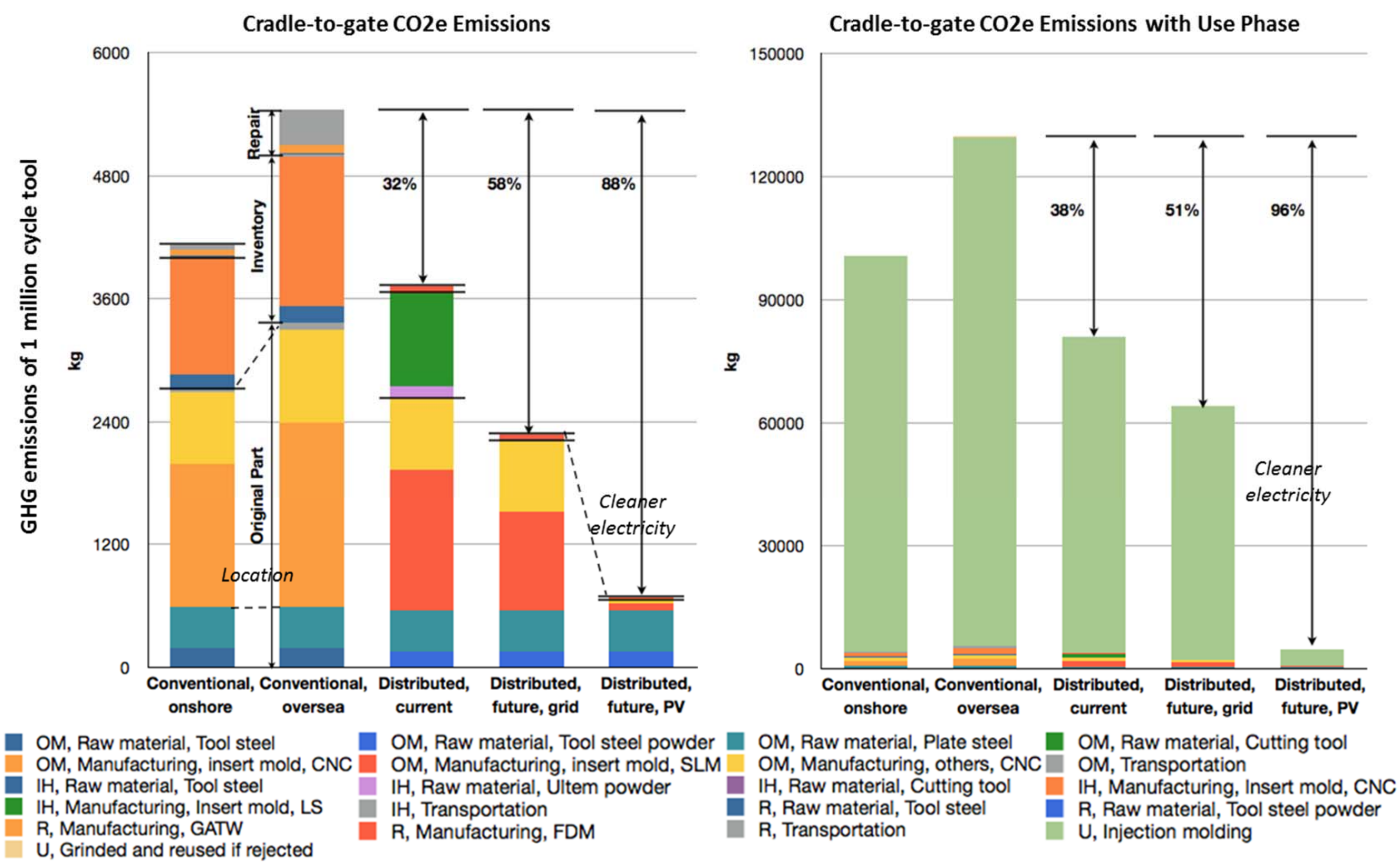
Distributed Manufacturing
Preliminary Results: Lead time

- More than 50% lead time savings (original mold & repair) could be achieved in the future if the AM building rates develop to 100 cm3/h (current ~25 cm3/h), which make "deliver over night" possible.
- Distributed AM saves time during tool repair, especially compared to overseas CM



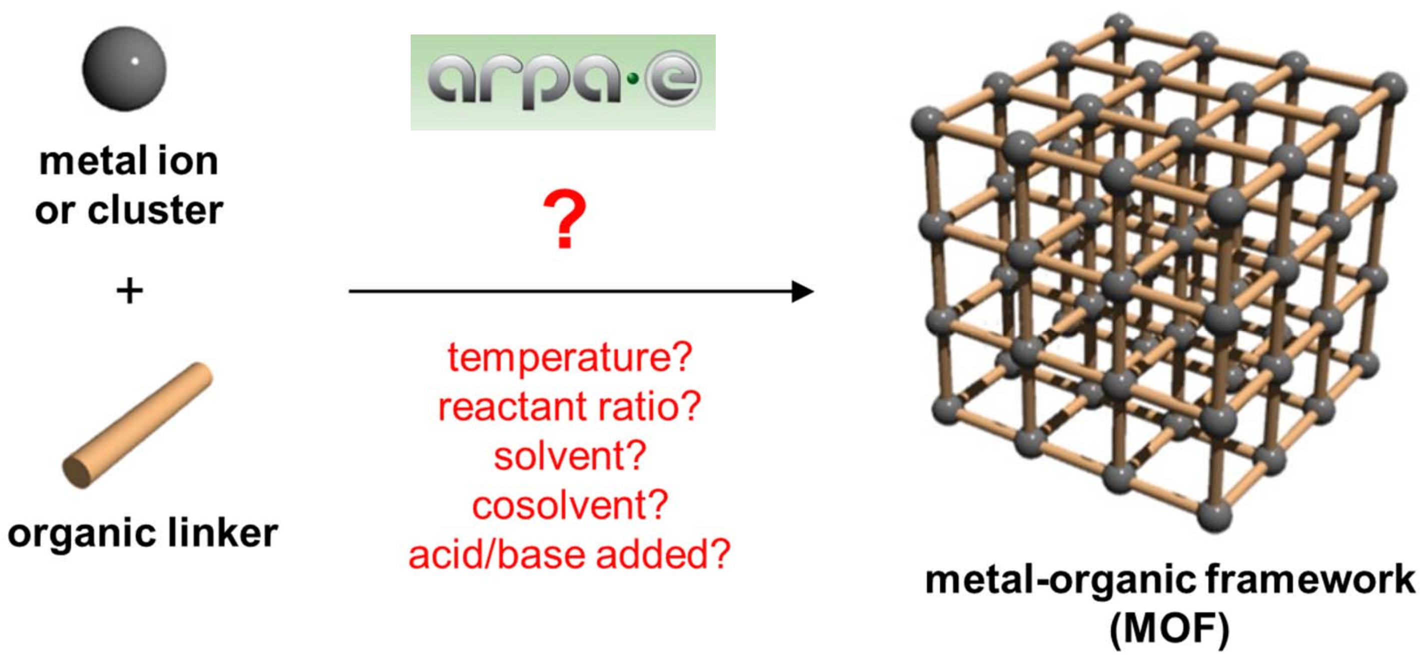
Distributed Manufacturing
Preliminary Results: GHG emissions

- Similar to primary energy, less inventory holding and technology improvement would reduce GHG emissions
- Renewable distributed generation systems (i.e. PV and wind) would save significant GHG emissions



Guiding R&D decisions in real time

Metal organic frameworks (MOFs) for carbon capture from coal-fired power plants



Sathre, R., and E. Masanet (2013). “Prospective Life-cycle Modeling of a CCS System Using Metal-Organic Frameworks for CO2 Capture.” *Royal Society of Chemistry (RSC) Advances*. In press.

Sathre, R., and E. Masanet (2012). “Energy and Climate Implications of CCS Deployment Strategies in the US Coal-fired Electricity Fleet.” *Environmental Science & Technology*. In press.

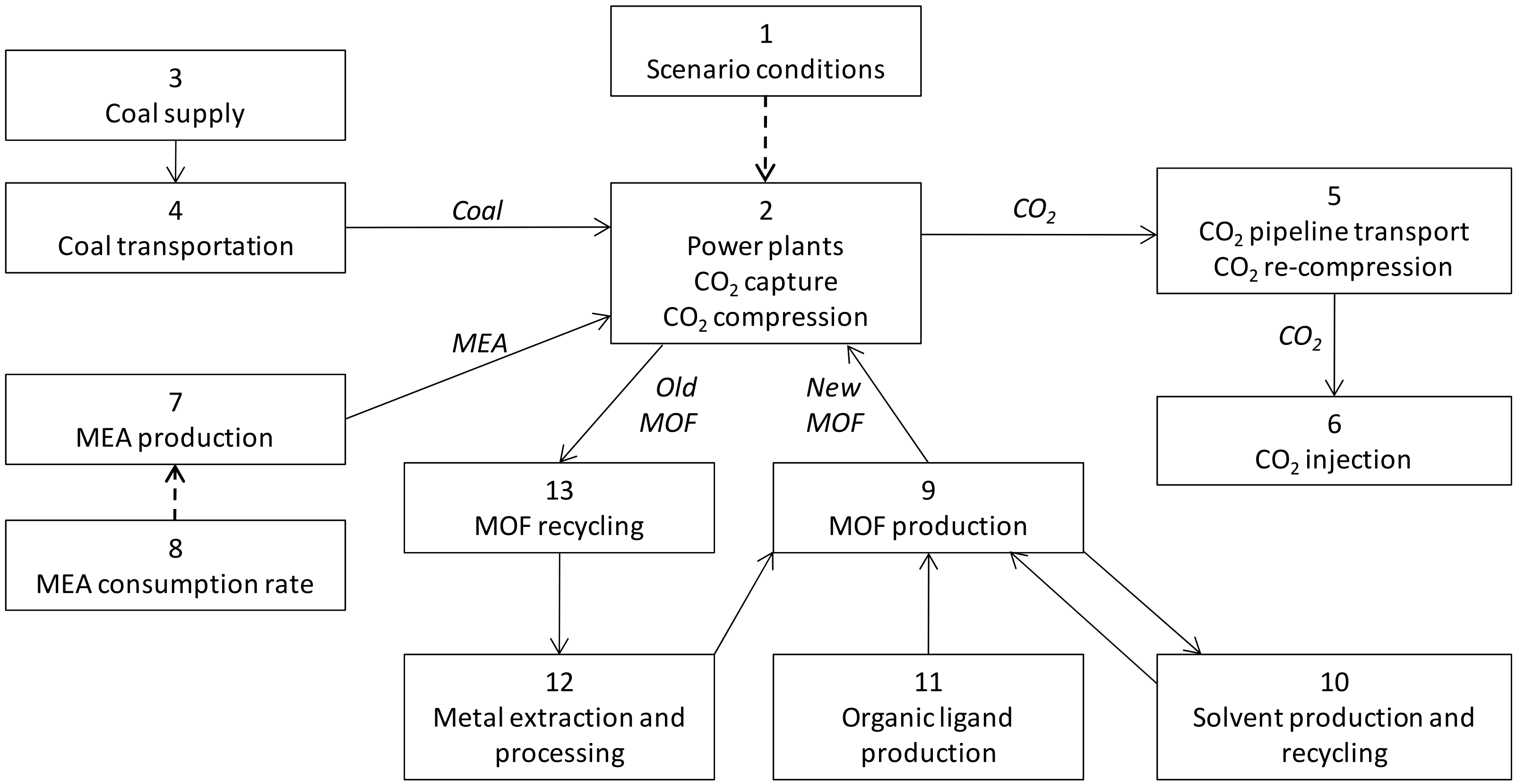
Sathre R, Chester M, Cain J, Masanet E. (2012). "A framework for environmental assessment of CO2 capture and storage systems." *Energy - The International Journal*. 37(1): 540-548.

McCormick

Northwestern Engineering

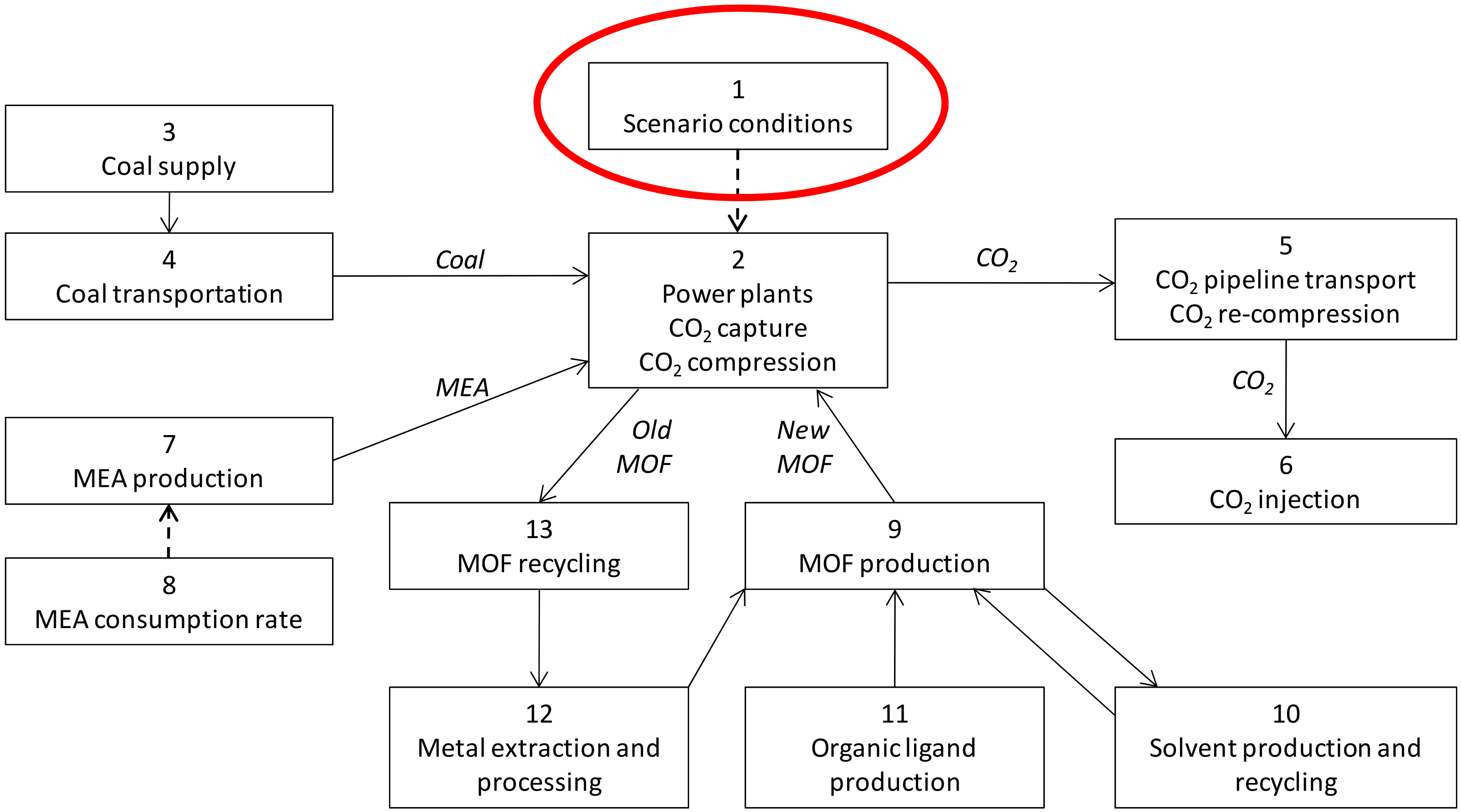
Dynamic Prospective Systems Model

- Describes system-wide energy use, GHG emissions, and cost
- Parameters describe uncertain and variable values



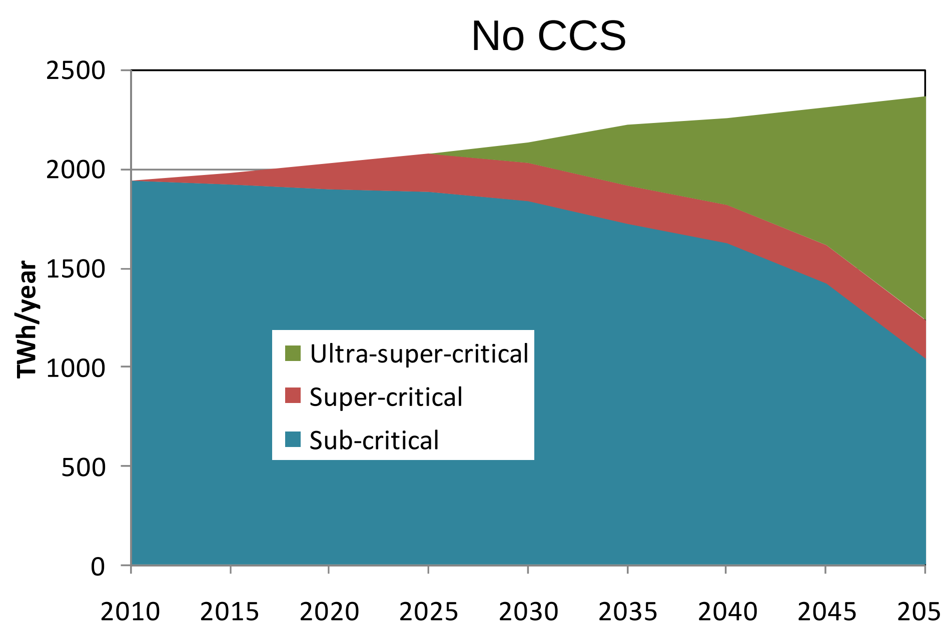
Scenario conditions

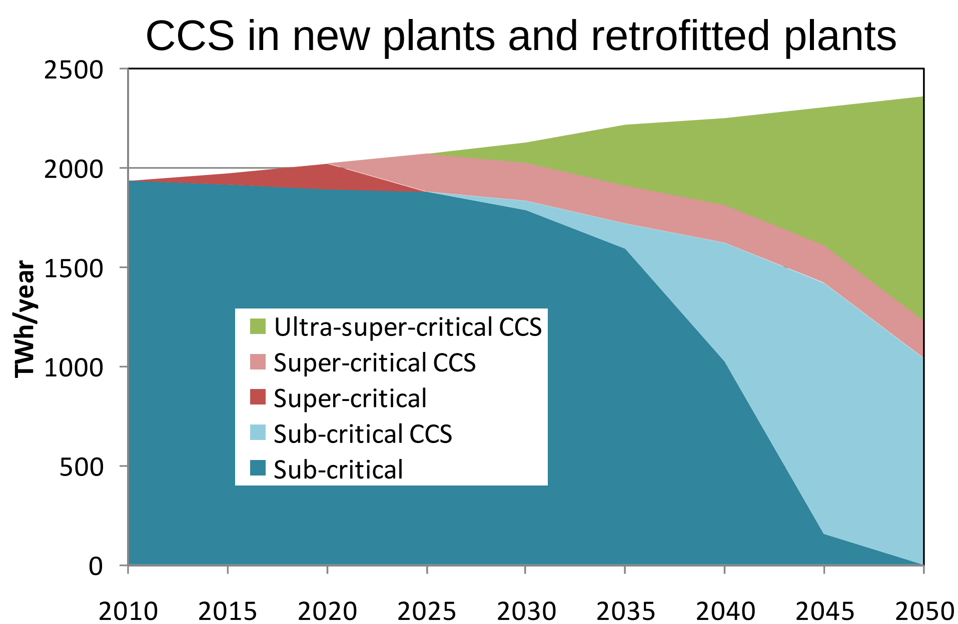
- Plausible development pathways for US coal-fired power fleet through 2050
- Defines time profile of annual electricity production (TWh/year)



CCS deployment scenarios

- Development of US coal-fired power plant fleet through 2050
- Electricity demand through 2035 based on EIA (2010), extrapolated thereafter
- Retirement of existing plants based on Ventyx (2011)
- CCS available for deployment after 2020

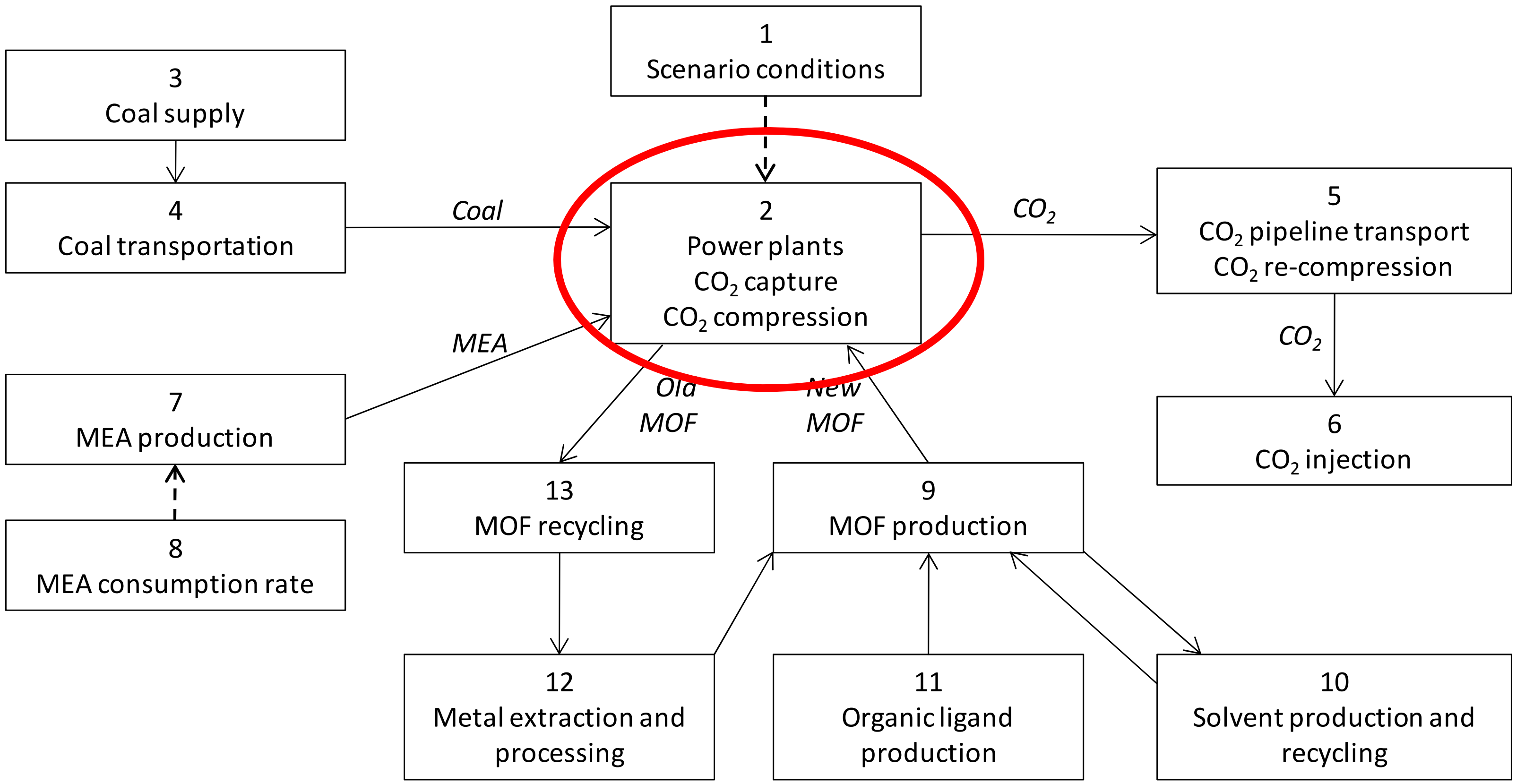




- Other scenarios (not shown) describe other deployment patterns
- Material presented today shows upper bound of CCS and MOF use in coal-fired plants

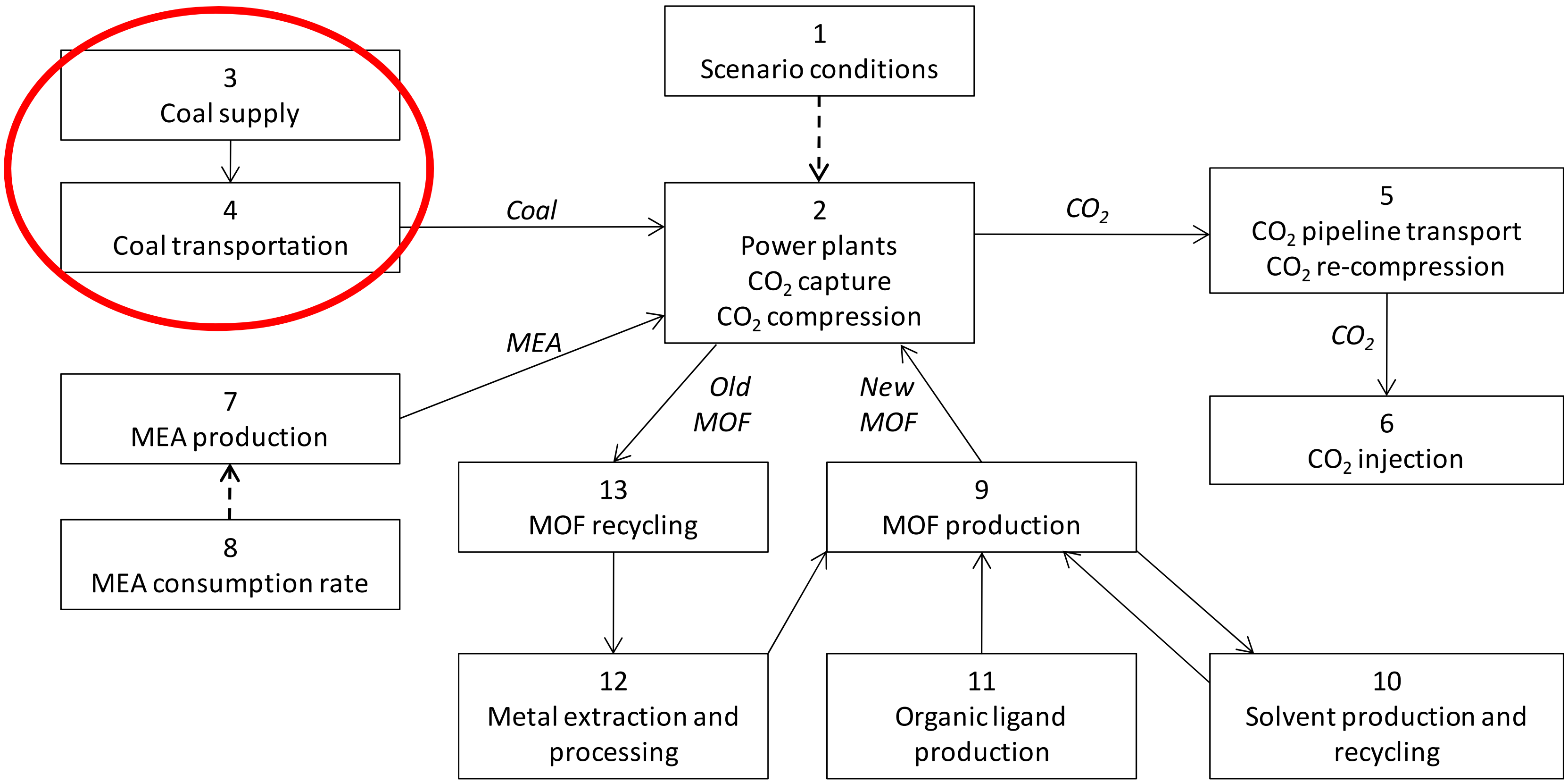
Power plants

- Performance characteristics of plants with and without carbon capture
- Improvement of generating efficiency over time



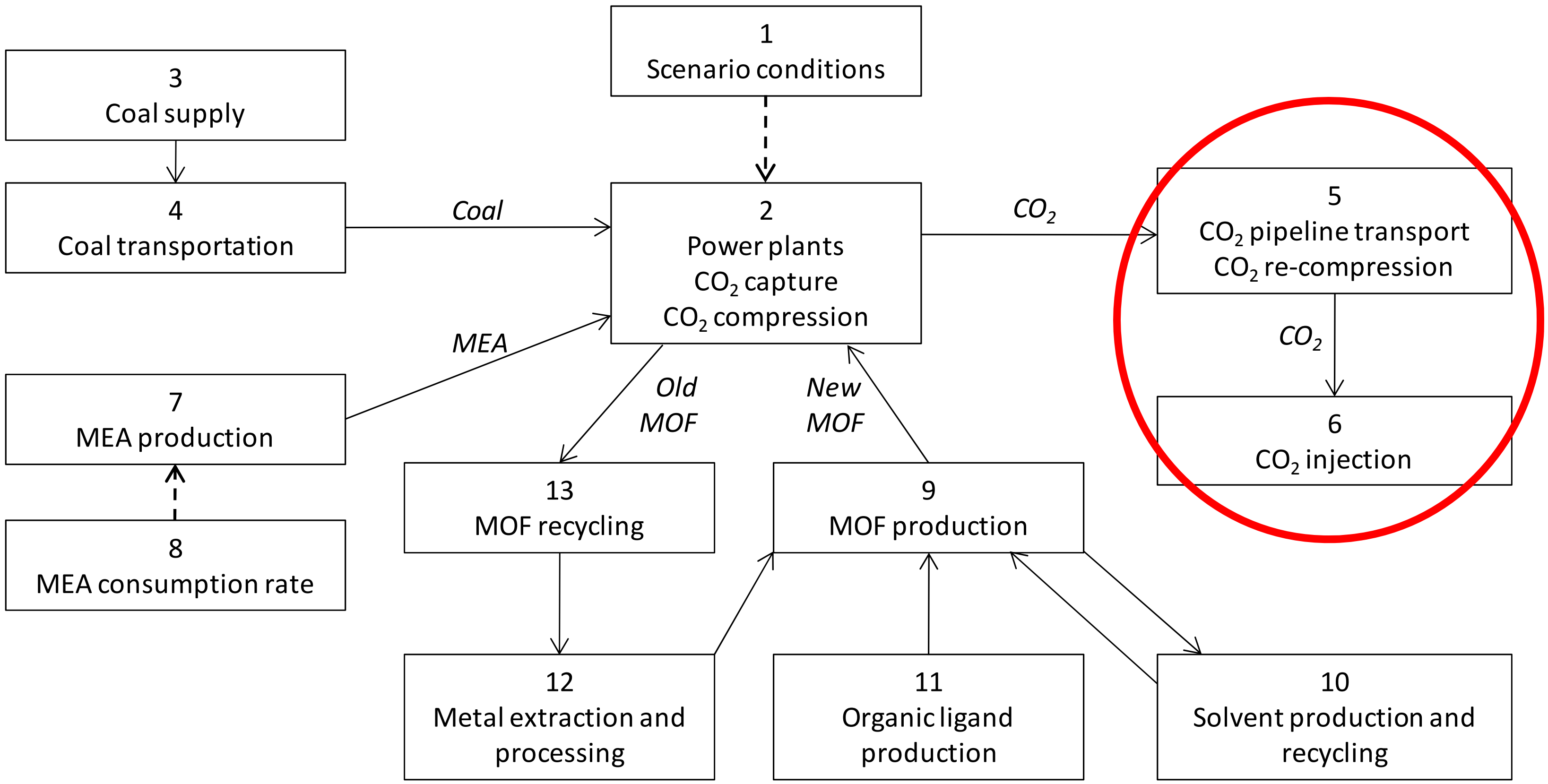
Coal supply and transportation

- Energy use and emissions for coal mining and rail transport
- Coal mine methane emissions



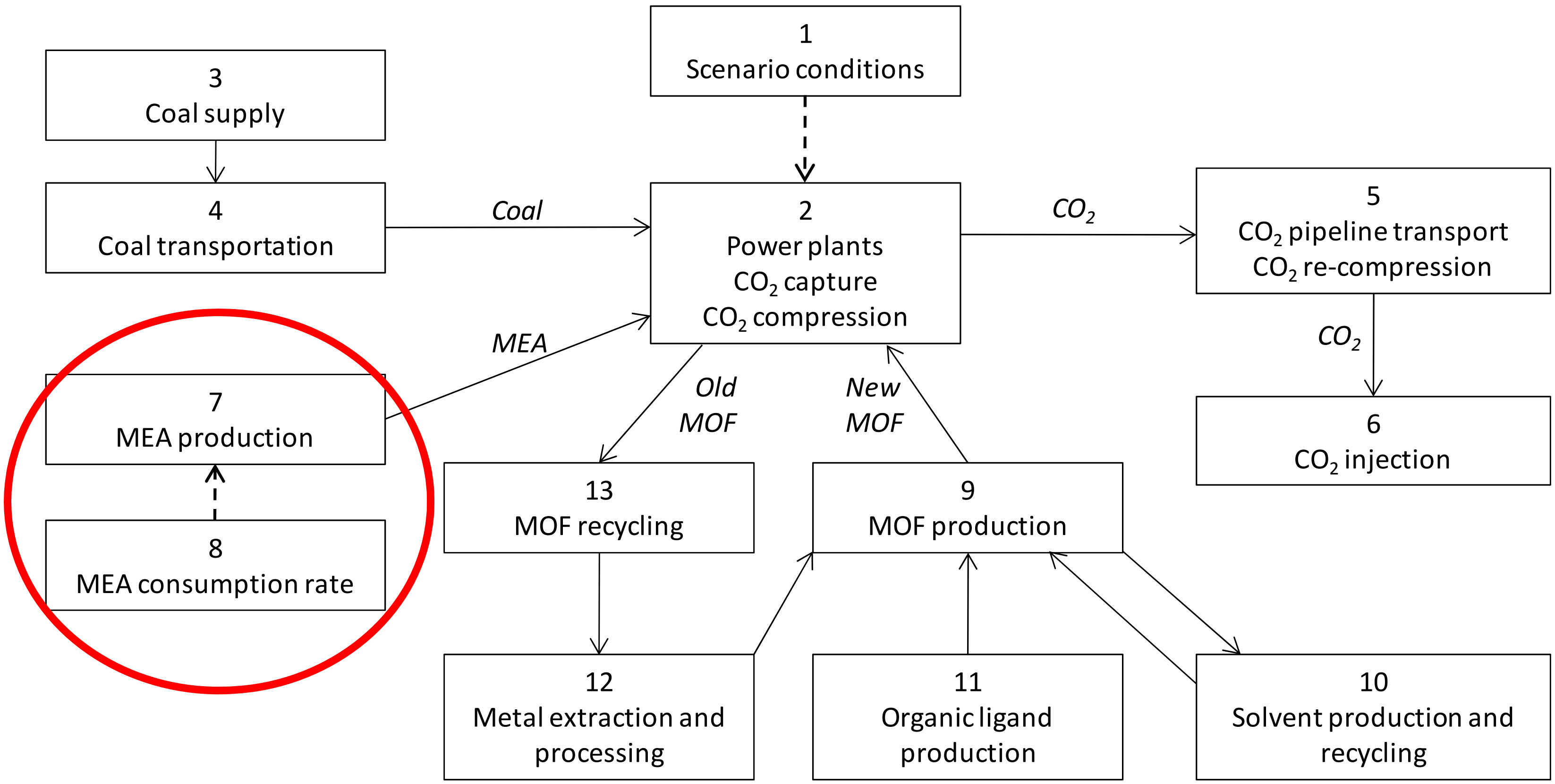
CO_2 transport and sequestration

- Construction and operation of CO_2 pipelines
- Injection in geologic formations



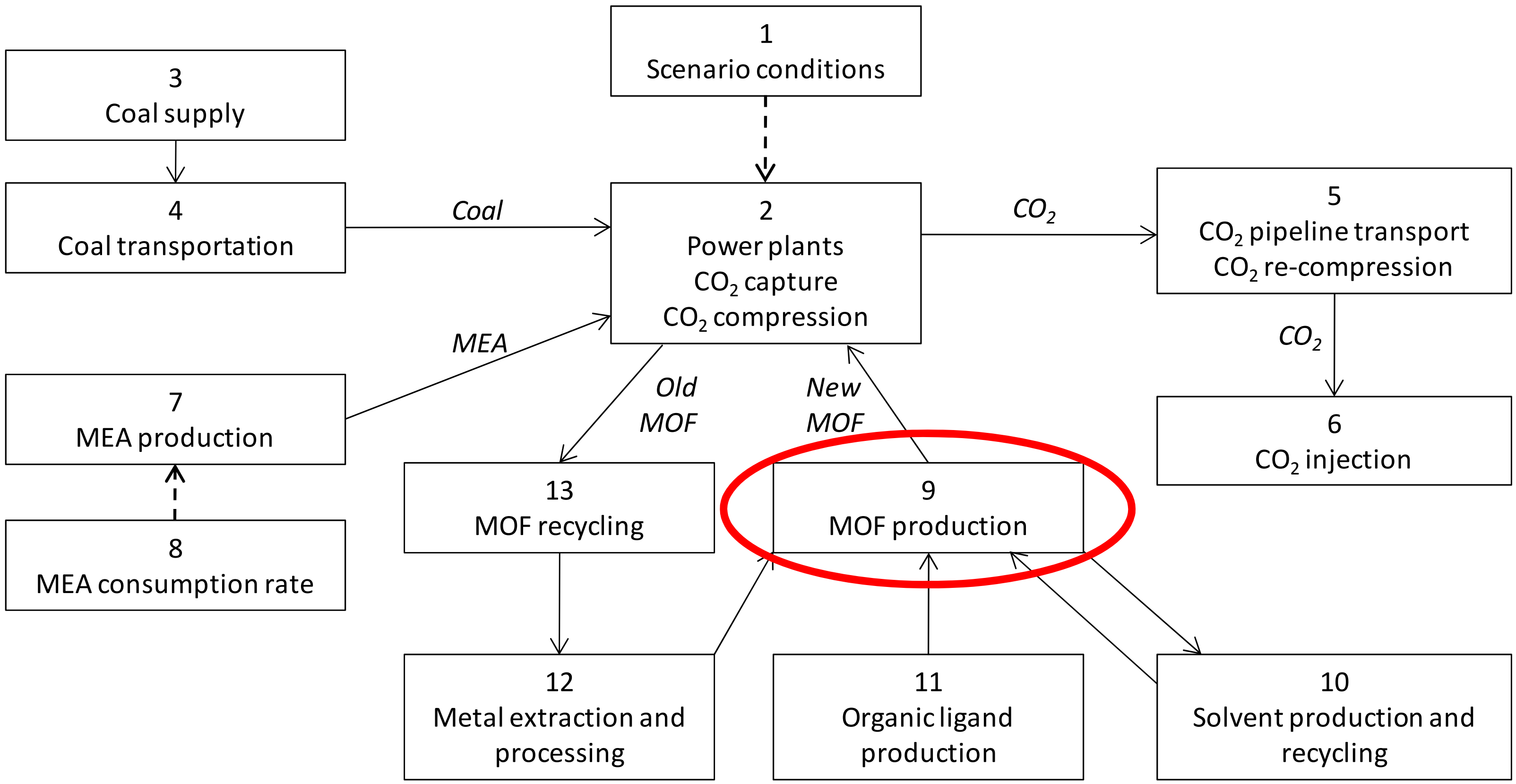
MEA production

- Baseline capture technology to which MOF is compared



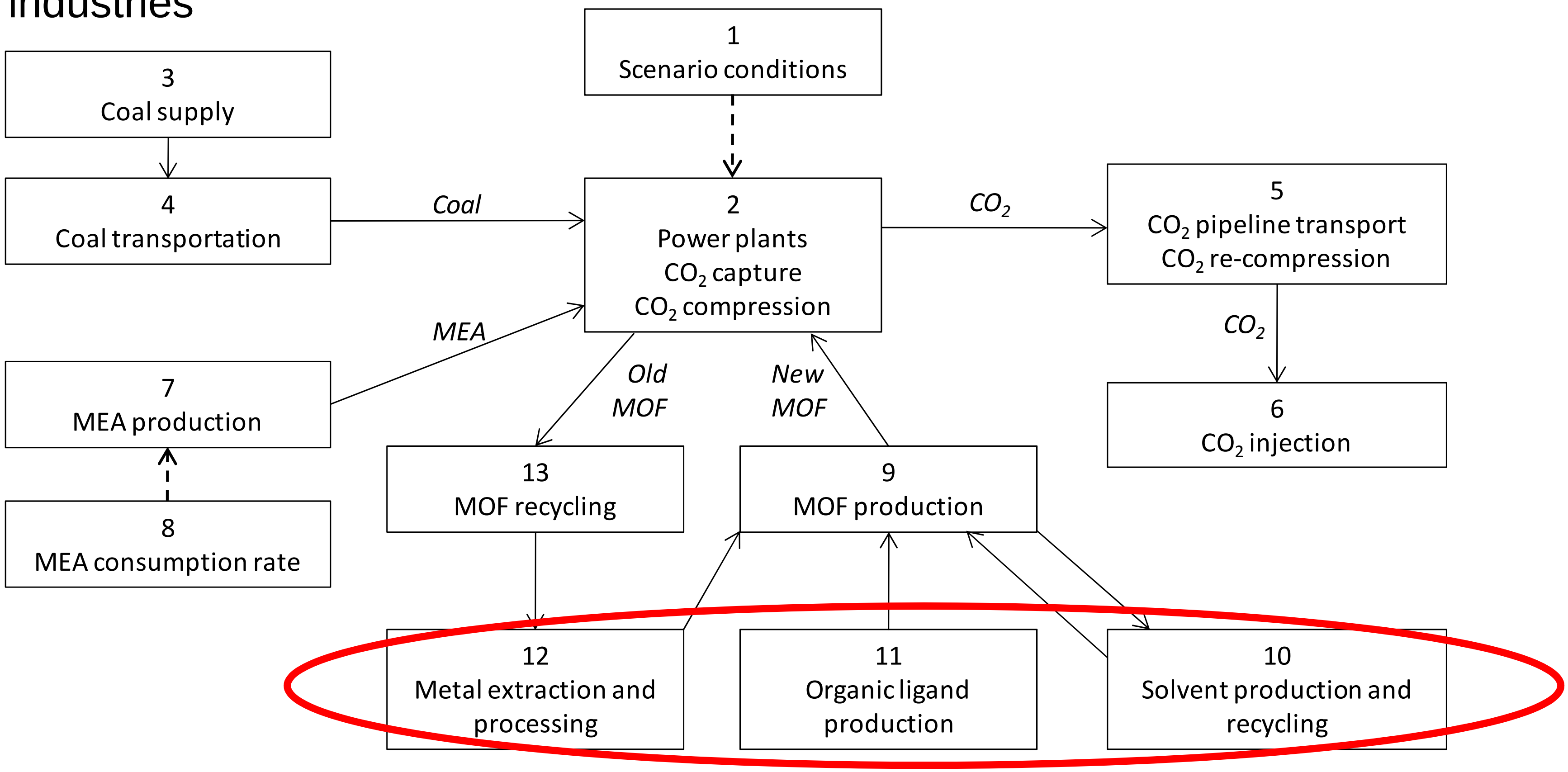
MOF production

- Projections of large-scale MOF synthesis
- Hybrid modeling using MOF-specific data plus proxy data from chemical industries



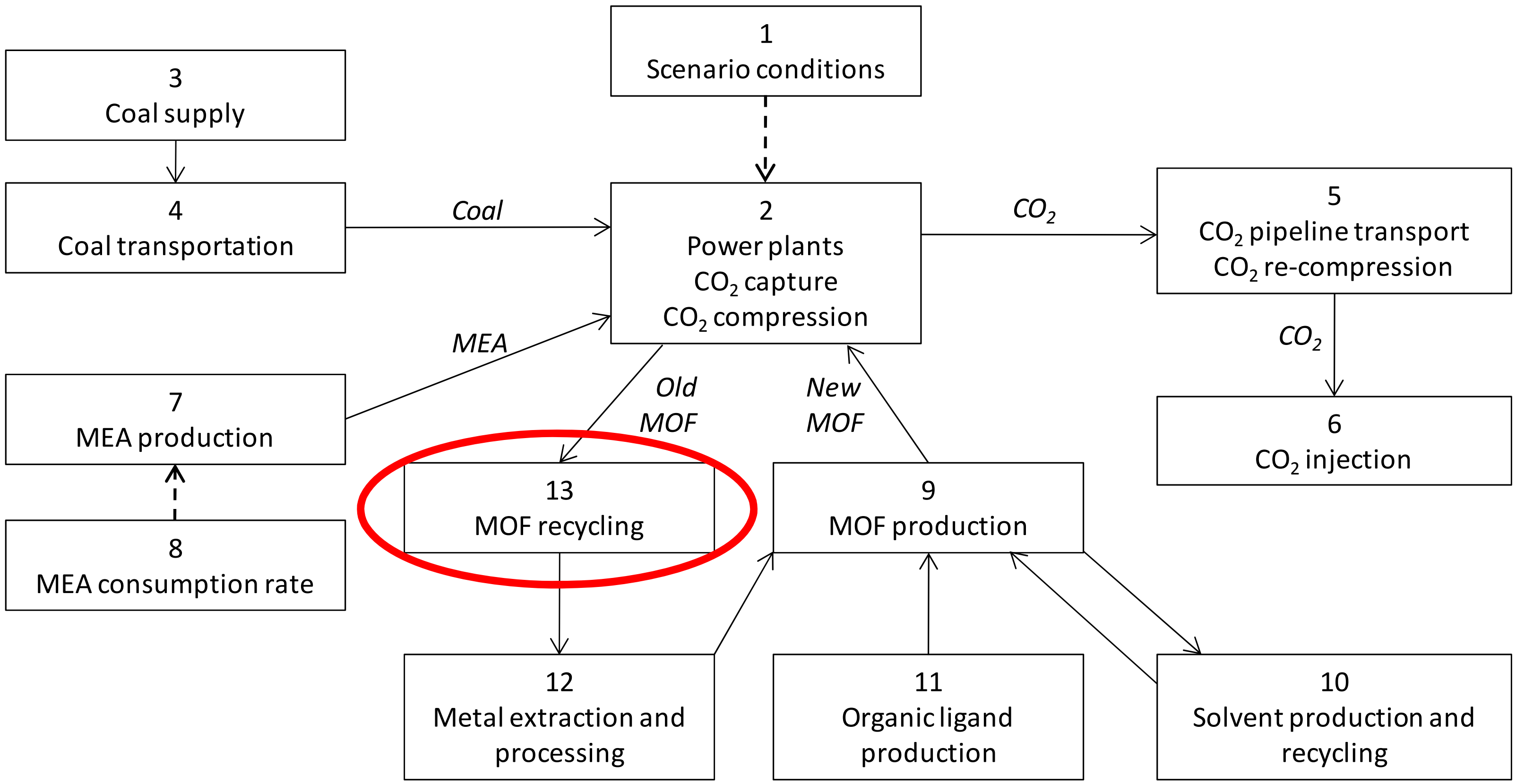
MOF input materials

- Potential material supply for large-scale MOF production
- Hybrid modeling using MOF-specific data plus proxy data from chemical industries

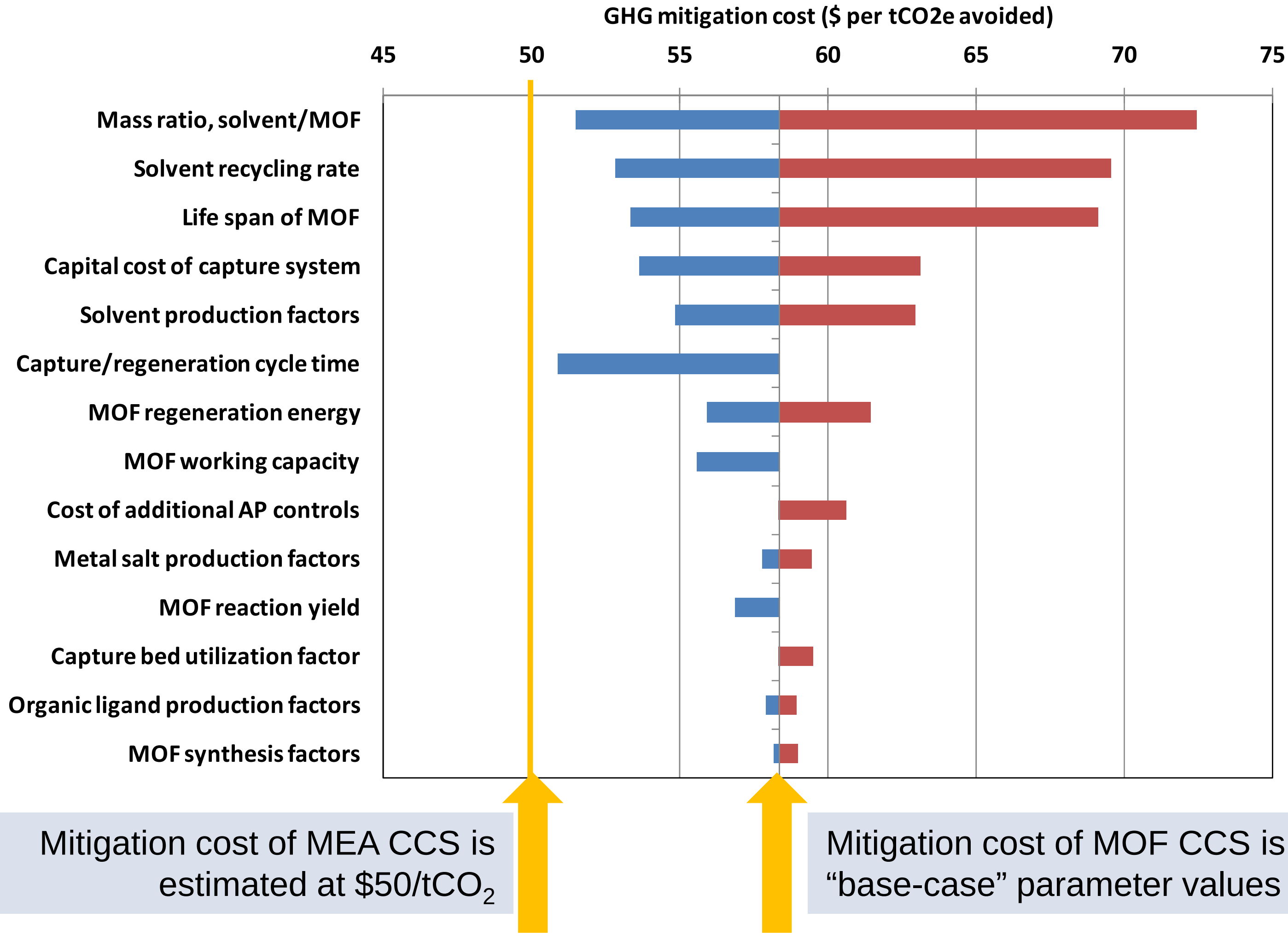


MOF recycling

- Metal recovery and reuse from post-use MOF material



GHG mitigation cost



Mitigation cost of MEA CCS is estimated at $50/tCO_2$

Mitigation cost of MOF CCS is $58/tCO_2$ with "base-case" parameter values

McCormick

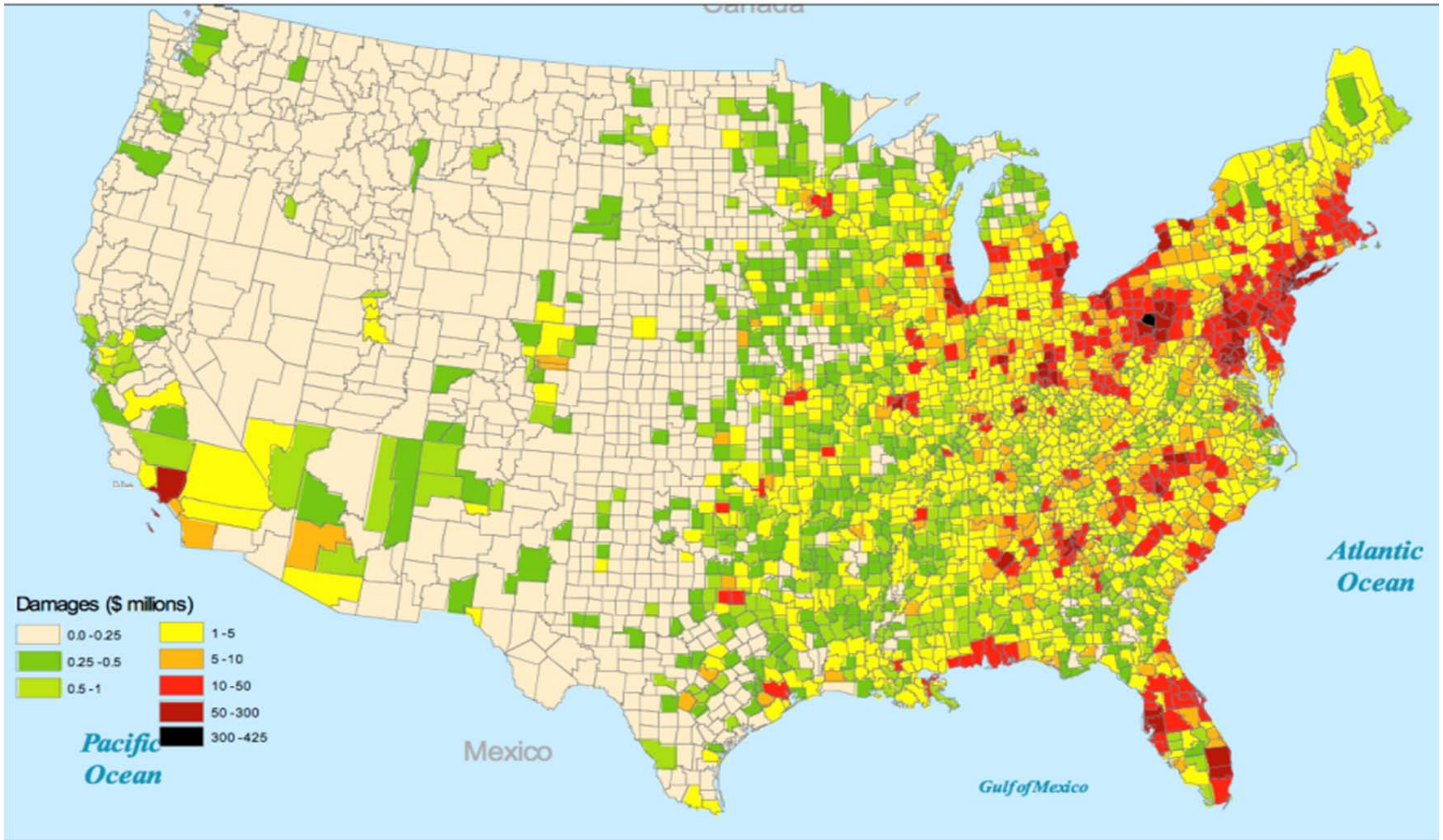
Northwestern Engineering

Environmental Impacts of Large-scale Photovoltaic (PV) Deployment

Pei Zhai[1], Peter Larsen[1], Dev Millstein[1], Surabi Menon[1], Eric Masanet[2]

[1] Lawrence Berkeley National Laboratory
[2] Northwestern University

Monetized Health Damage from Fossil-fuel Electric Power Generators



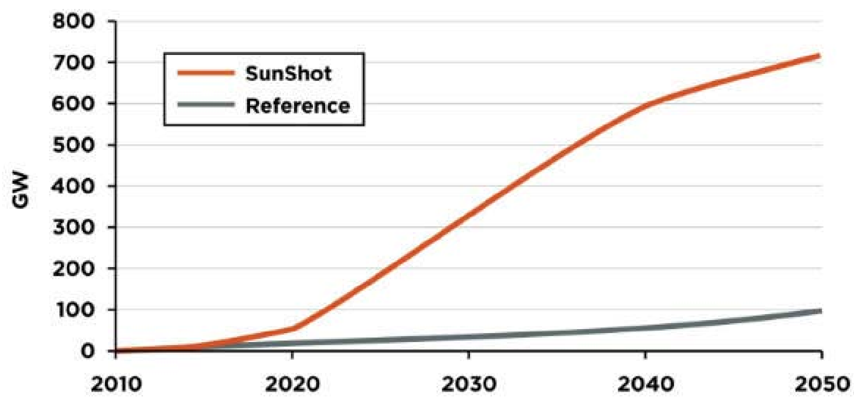
Source: NRC (2010)

McCormick

Northwestern Engineering

Research Motivations

- U.S. DOE SunShot Initiative, 13% solar (10% PV, 3% thermal) by 2030, 18% by 2050
- Large uncertainties in environmental and human health benefits of solar PV at the regional level:
  - Albedo effects on air chemistry and quality
  - Local population and demographic characteristics
  - Evolution of the energy system
    - Energy supply characteristics
    - Demand profiles
    - Effects of efficient technology deployment



Zhai, P., Larsen, P., Millstein, D., Menon, S., and E. Masanet (2013). "The Potential for Avoided Emissions from Photovoltaic Electricity in the United States." *Energy – The International Journal*. Volume 47, Issue 1, Pages 443–450.

Scenarios of the U.S. PV deployment

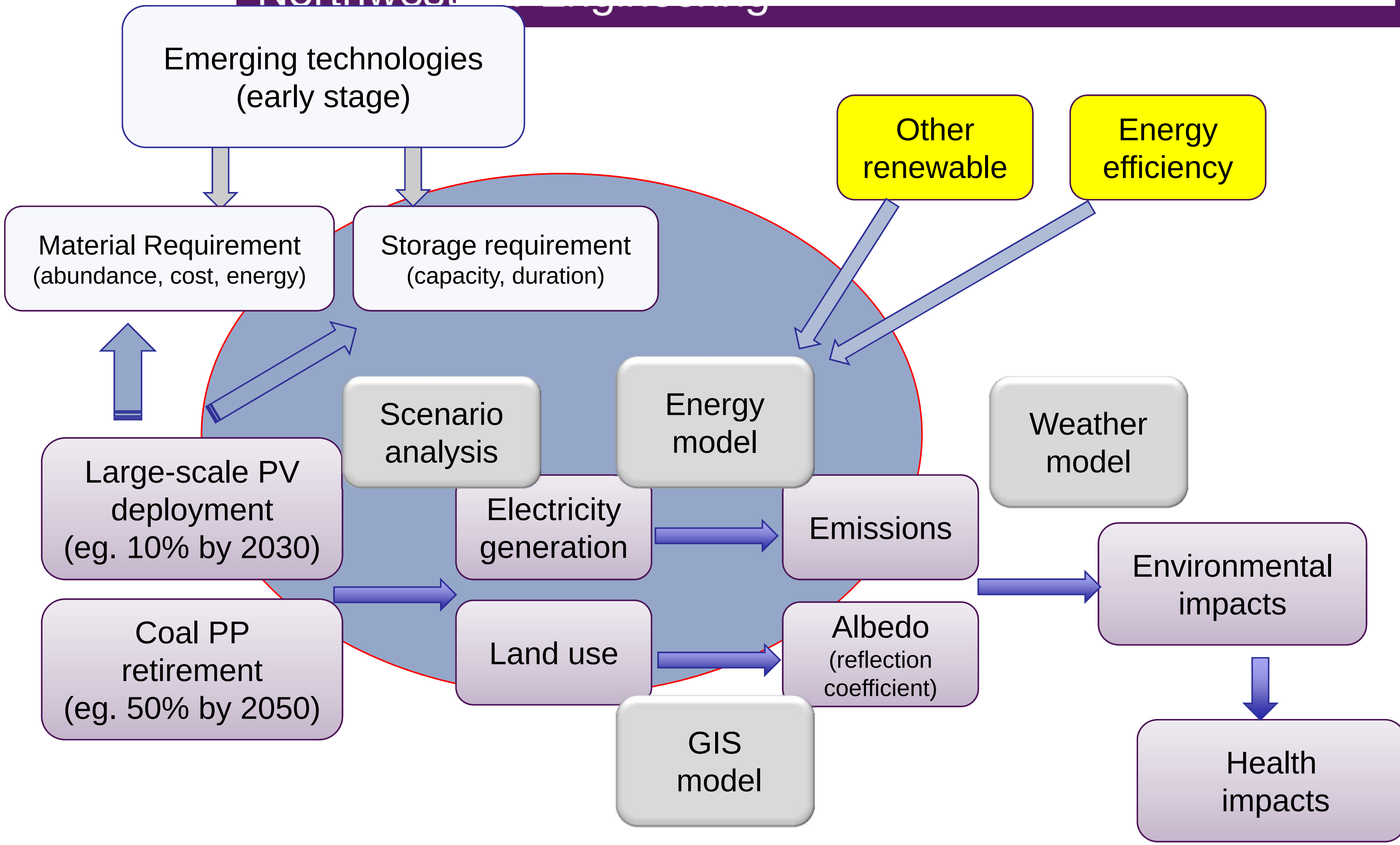
Year	PV penetration	PV capacity (GW)	PV generation (TWh)	Land use (km2)
2010	0.05%	1	2	6
2020	5%	100	197	624
2030	10%	200	395	1247
2040	15%	300	593	1870
2050	20%	400	790	2494

Assumptions:

- PV system capacity factor is 22.6% (1-axis tracking)
- PV module efficiency is 16%

Note: Land of California is 414,000 km2

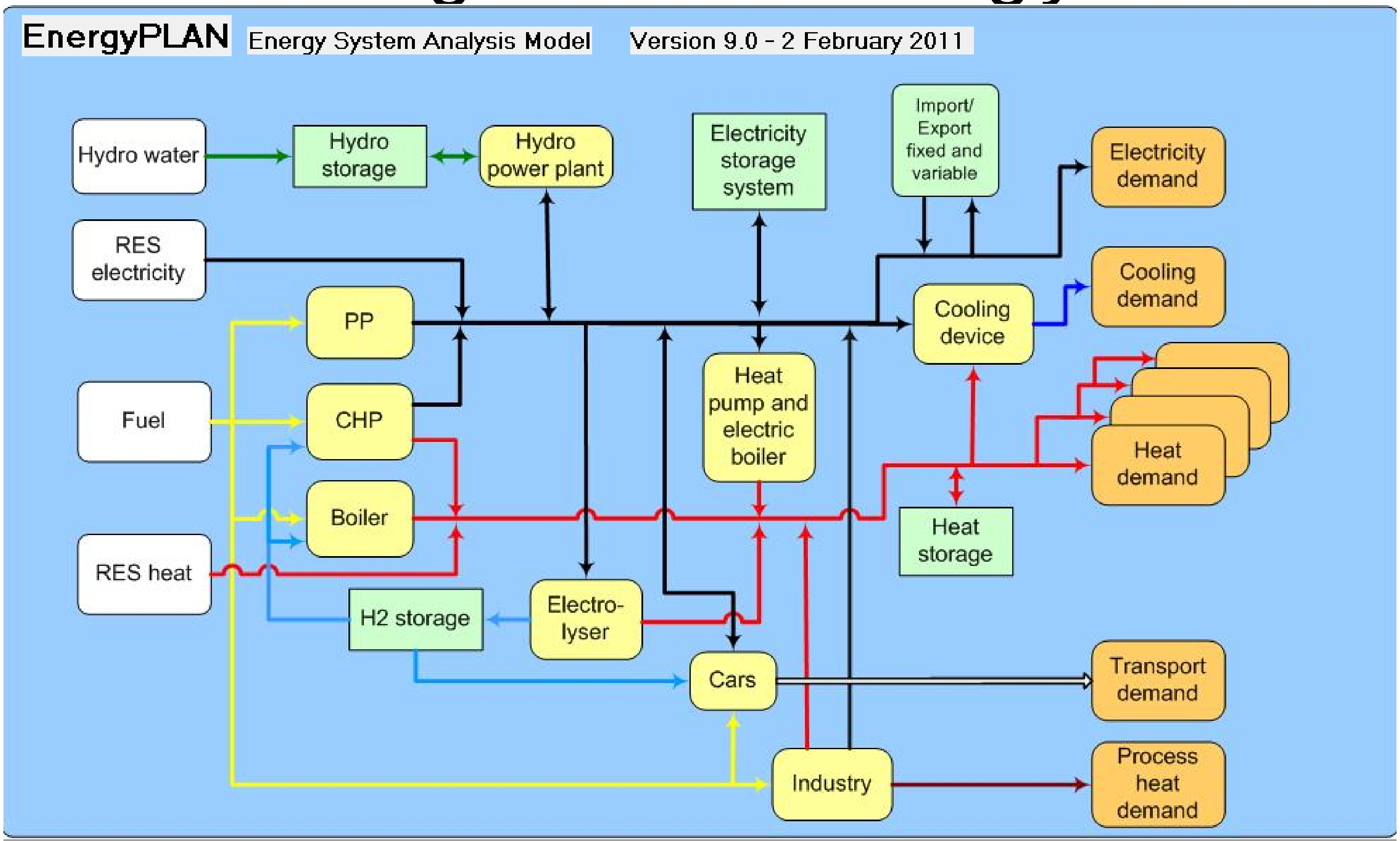
Research framework and models



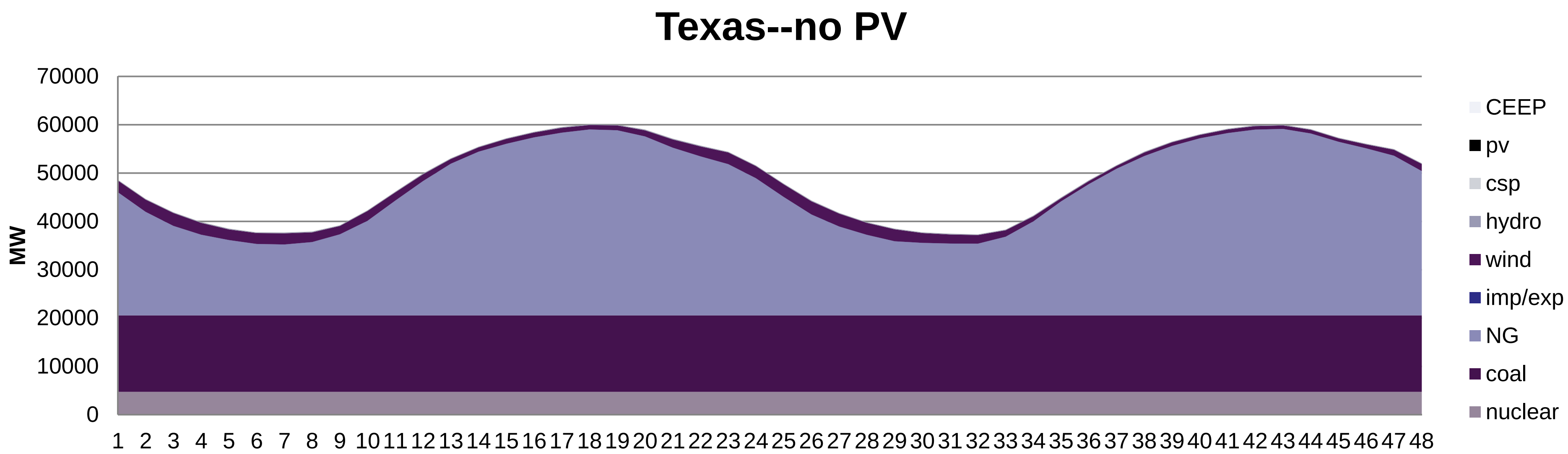
McCormick

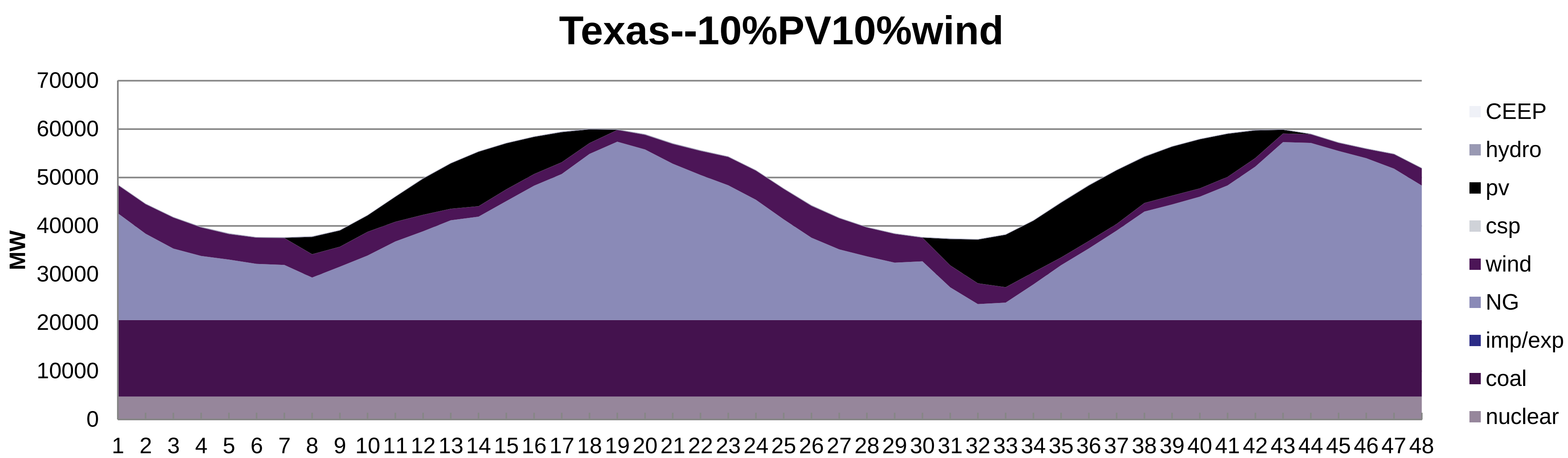
Northwestern Engineering

Modeling tool – EnergyPlan9.0



Understanding hourly generation is important to renewable energy integration, energy efficiency analysis





Results: PV benefits?

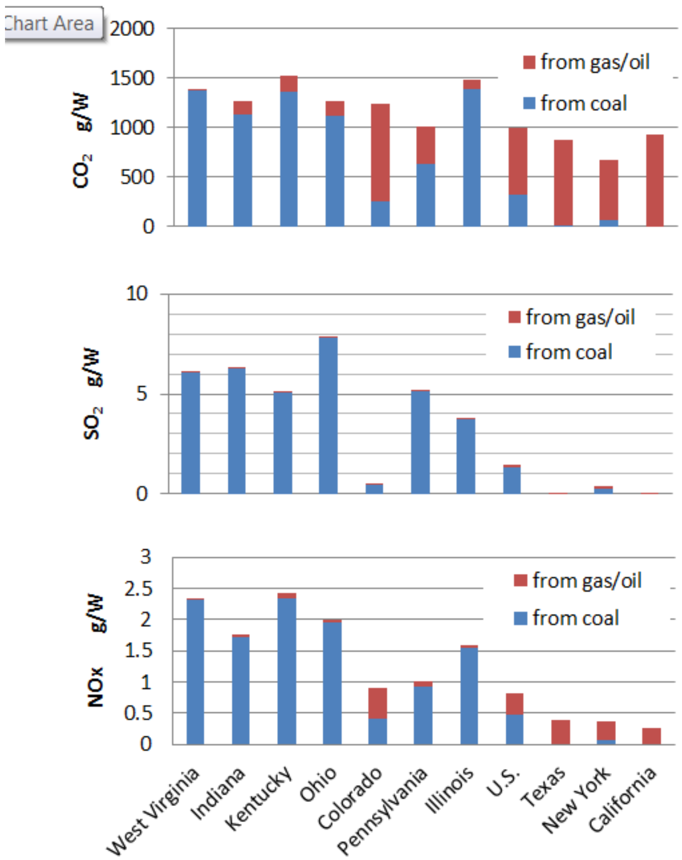


Figure 1: Avoided emission per unit (from coal plants and gas plants) after 10% PV penetration by type of fuel displacement (either coal or natural gas/oil): (a) CO_2; (b) SO_2; (c) NO_x

McCormick

Northwestern Engineering

Prospective techno-economic life-cycle systems analysis for sound policy

ERSAL policy focus:

Accelerating deployment

An economist and his friend are walking, and the friend spies a $20 bill on the sidewalk. The friend says “Hey, $20! Let’s pick it up.”

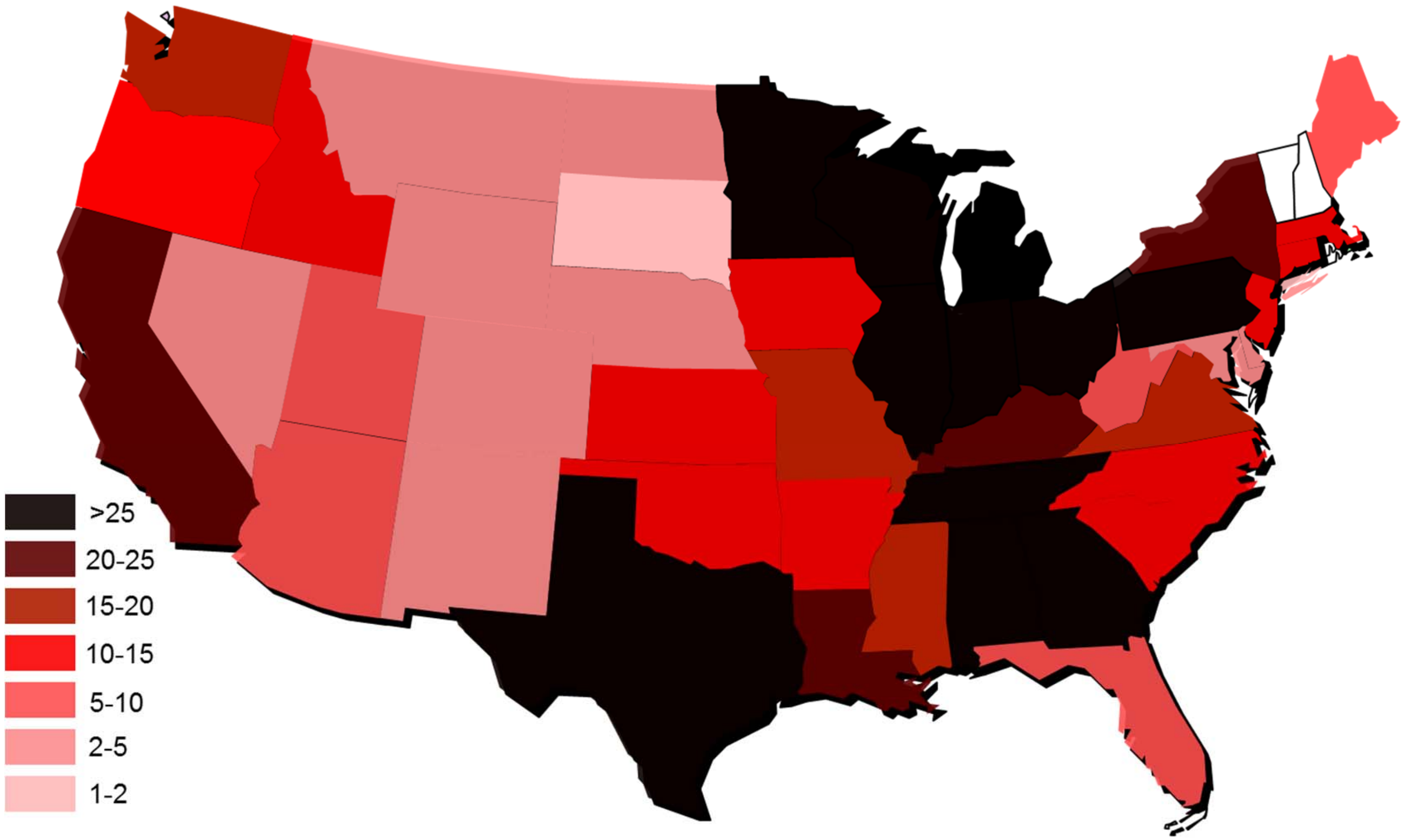
The economist replies “Leave it. If it were real, somebody would have picked it up already.”

McCormick

Northwestern Engineering

U.S. DOE Energy Savings Audits (ESAs) Performed

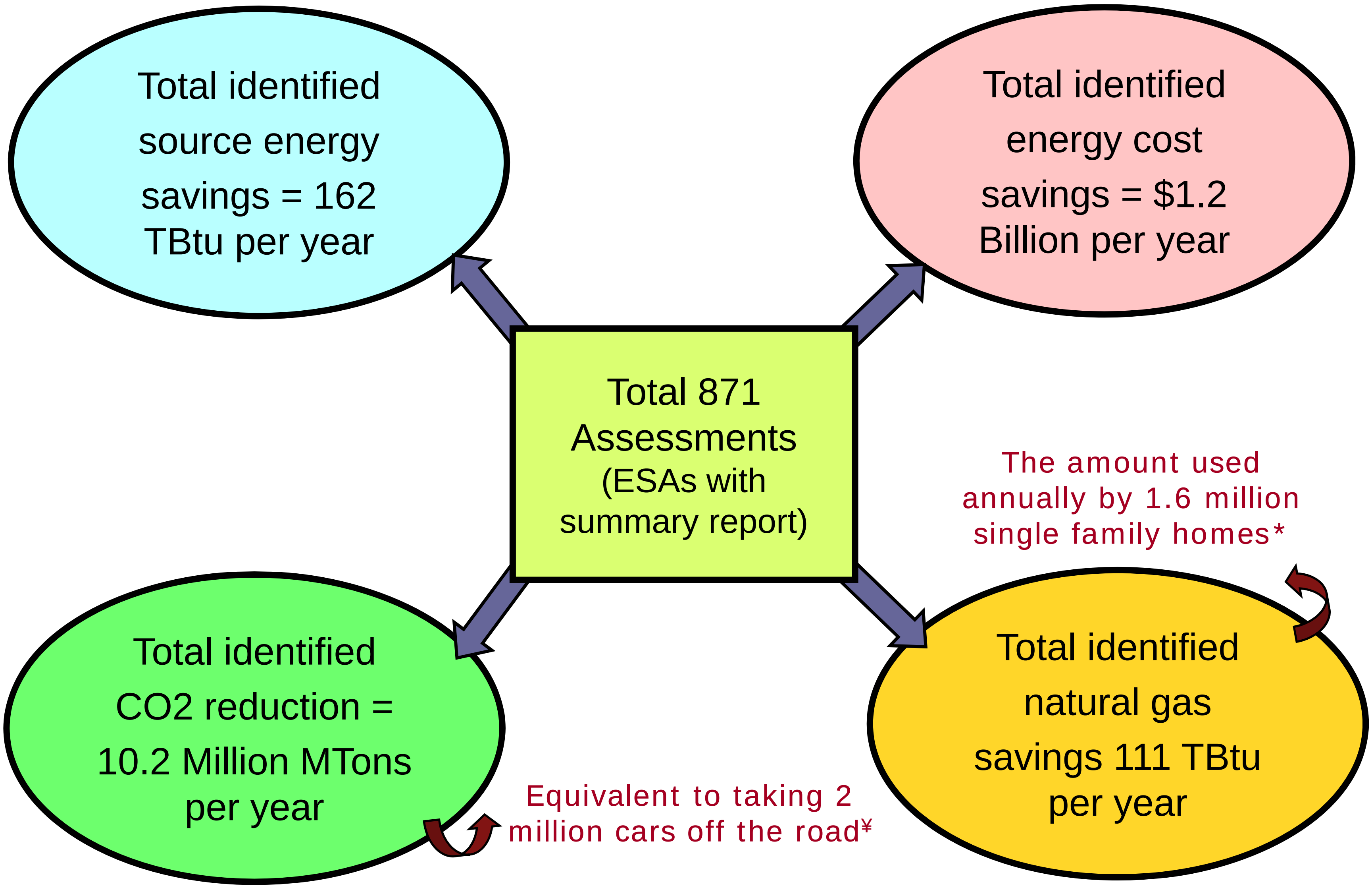
Total 871 ESAs (Year 2006 – 2010)



Source: Oak Ridge National Laboratory

McCormick

Northwestern Engineering



Source: Oak Ridge National Laboratory

Source energy:
Implemented: 27.6 TBtu/year
In-Progress: 25.0 TBtu/year
In-Planning: 30.3 TBtu/year

Energy cost:
Implemented: $163 Million/year
In-Progress: $173 Million/year
In-Planning: $252 Million/year

Total 624 Assessments
(ESAs with follow-up information)

Based on different reporting timeframes (6, 12 and 24 months follow-up calls)

CO2 reduction:
Implemented: 1.78 Million MTons/year
In-Progress: 1.52 Million MTons/year
In-Planning: 1.92 Million MTons/year

Source: Oak Ridge National Laboratory

Identified source energy savings for 624 ESAs is 114 TBtu/yr and cost savings are $858 million/yr.

Why are Large Plants Passing on Low-Cost Energy Efficient Technologies?

Common barriers to industrial energy efficiency include:

Financial

- Restrictive budget and fiscal criteria
- Energy costs might represent a small fraction of production costs
- Short-term revenue generation often takes priority
- Lack of cross-departmental cooperation

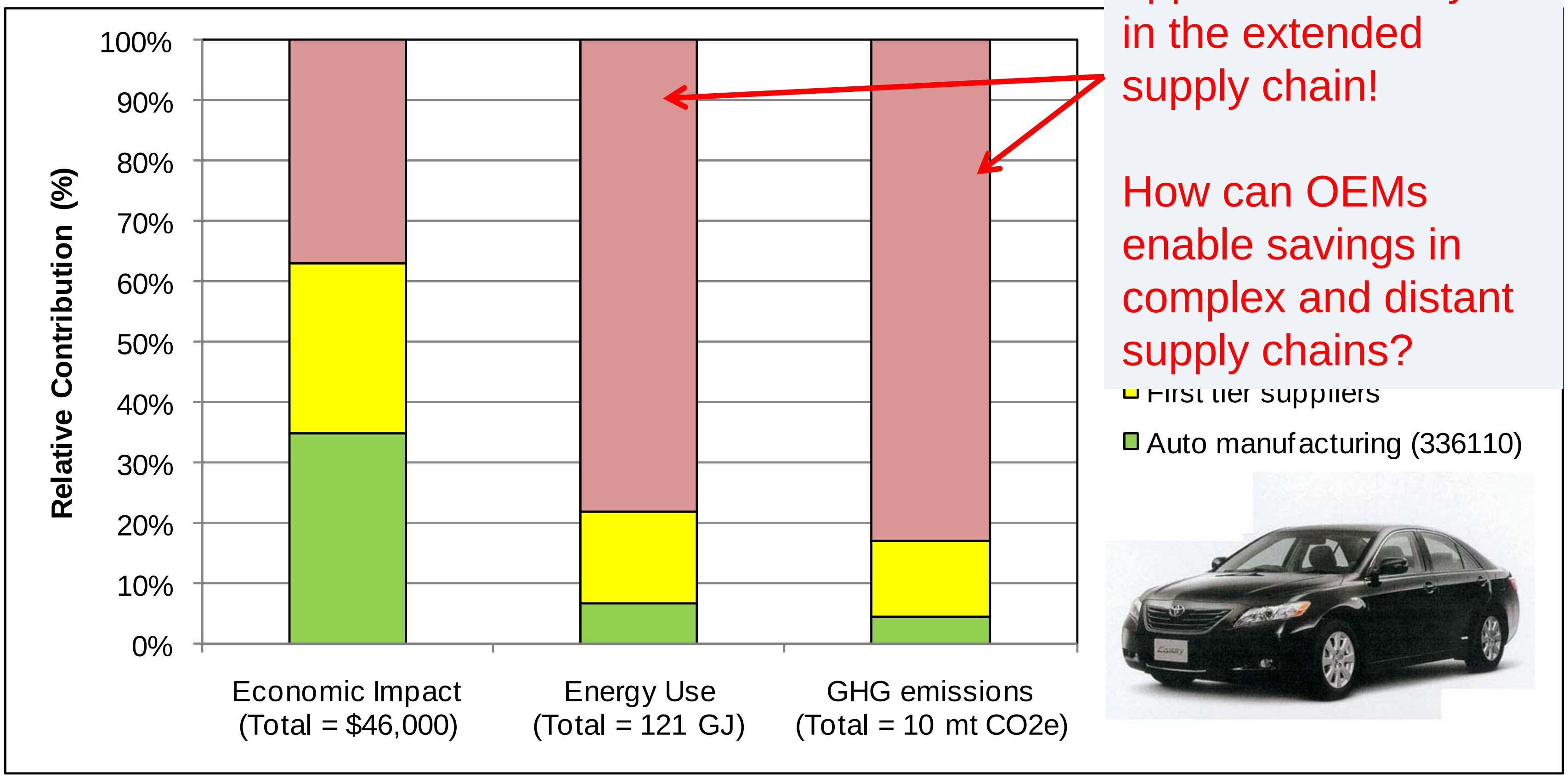
Information

- Lack of staff and management awareness
- Lack of resources (time, money, and skills) to identify and pursue energy efficiency opportunities
- Lack of information on key opportunities for government and utility company policies and incentive programs

Source: Russell, C. (2005). Barriers to Industrial Energy Cost Control: The Competitor Within. Chemical Processing. June 8th.

OEM leverage

**Economic Impact, Energy Use, and GHG Emissions A[...]
Manufacture of an Average Midsize U.S. Pas[...]**



Most reduction opportunities may be in the extended supply chain!

How can OEMs enable savings in complex and distant supply chains?

Source:

Source: Sathaye, J.A., Lecocq, F., Masanet, E., Najam, A., Schaeffer, R., Swart, R., and H. Winkler (2009). “Opportunities to Change Development Pathways Towards Lower Greenhouse Gas Emissions Through Energy Efficiency.” Journal of Energy Efficiency, Volume 2, Number 4.

Supply Chain Energy Management: A Promising Approach?

Motivations

- Recognition that the environmental footprints of many products extend deep into the producing sector's supply chain
- Increasing demand for footprint data by retailers and customers

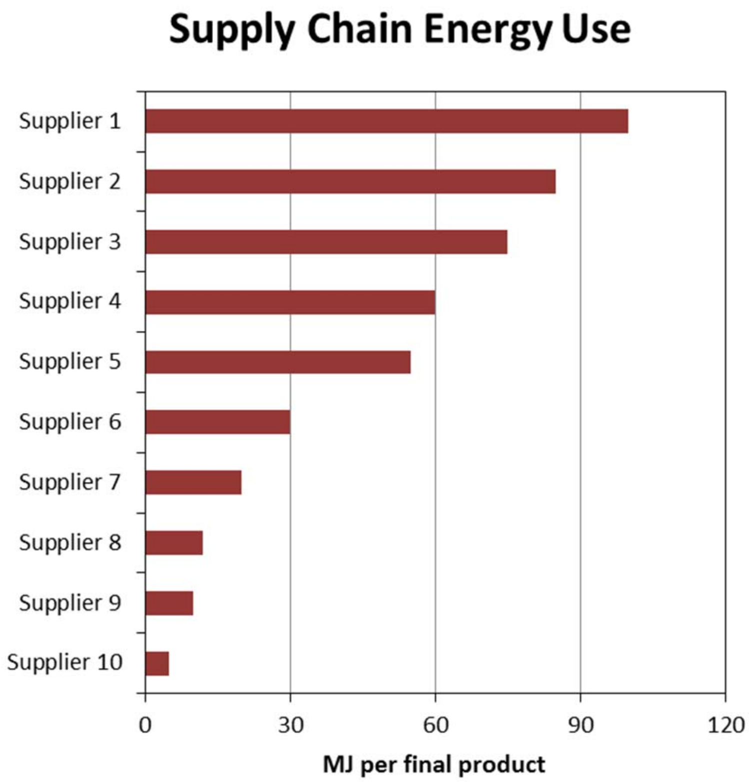
Approaches

- Sponsored energy audits
- Technical assistance
- Financial incentives
- Benchmarking and target setting
- Initiatives by Pepsico, IKEA, and many others

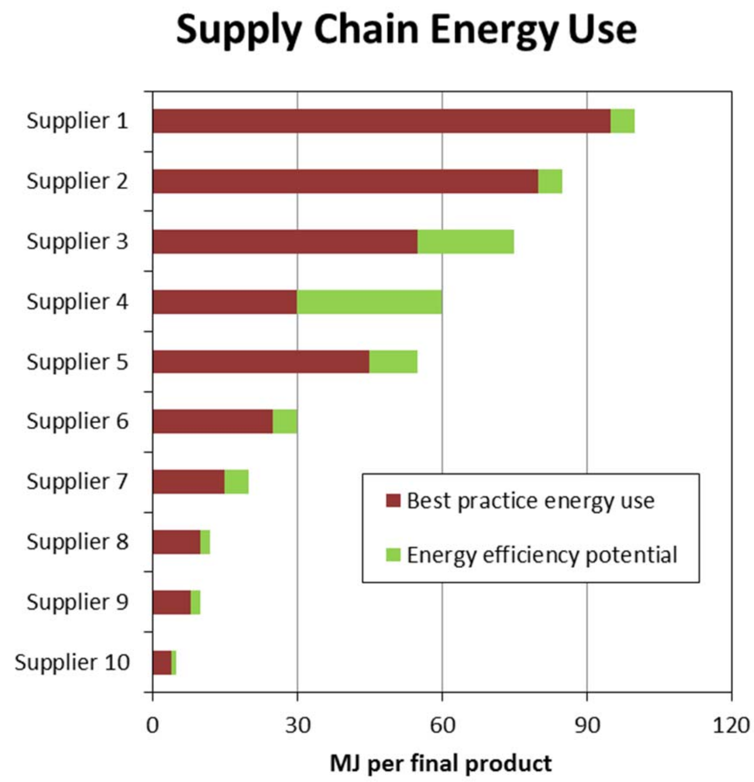
Research Question

- **So we have a supply chain environmental footprint** … **now what**? What and where are *specific* opportunities for reducing this footprint along the supply chain, and at what level of cost?

We can do this:



Supply chain initiatives require this:



Input-Output Life-Cycle Analysis

	Input to sectors				Intermediate output O	Final demand F	Total output X
Output from sectors	1	2	3	n			
1	X_{11}	X_{12}	X_{13}	X_{1n}	O_1	F_1	X_1
2	X_{21}	X_{22}	X_{23}	X_{2n}	O_2	F_2	X_2
3	X_{31}	X_{32}	X_{33}	X_{3n}	O_3	F_3	X_3
n	X_{n1}	X_{n2}	X_{n3}	X_{nn}	O_n	F_n	X_n
Intermediate input I	I_1	I_2	I_3	I_n			
Value added V	V_1	V_2	V_3	V_n		GDP	
Total input X	X_1	X_2	X_3	X_n			

$\sum X_{ij} + F_i = X_i;$ $X_i = X_j;$ using $D_{ij} = X_{ij} / X_j$

$\sum (D_{ij}*X_j) + F_i = X_i$

in vector/matrix notation:

$D*X + F = X \Rightarrow$ $F = [I - D]*X$

or $X = [I - D]^{-1}*F$

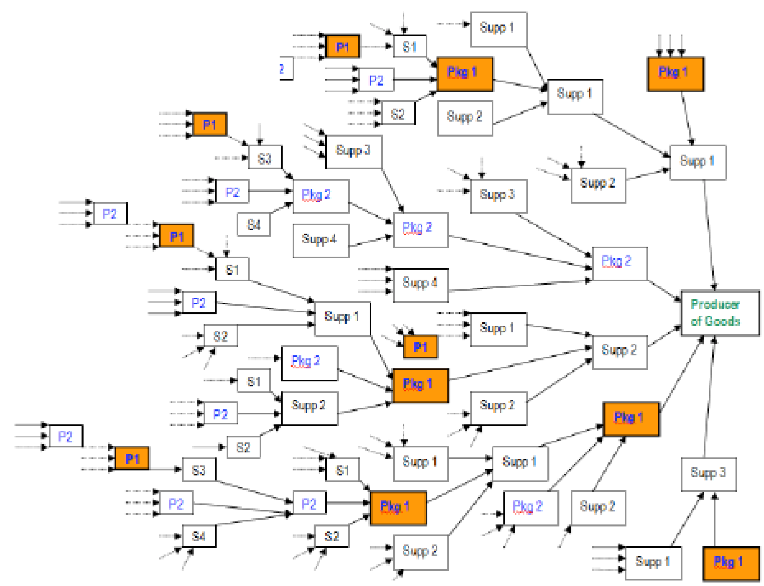
IO Sector-Level Environmental Coefficients

$\frac{\text{Annual GHG emissions (kg)}}{\text{Annual output } X (\$)}$

↓

$\frac{\text{kg } CO_2\text{e}}{\$}$

Supply Chain Contribution Analysis

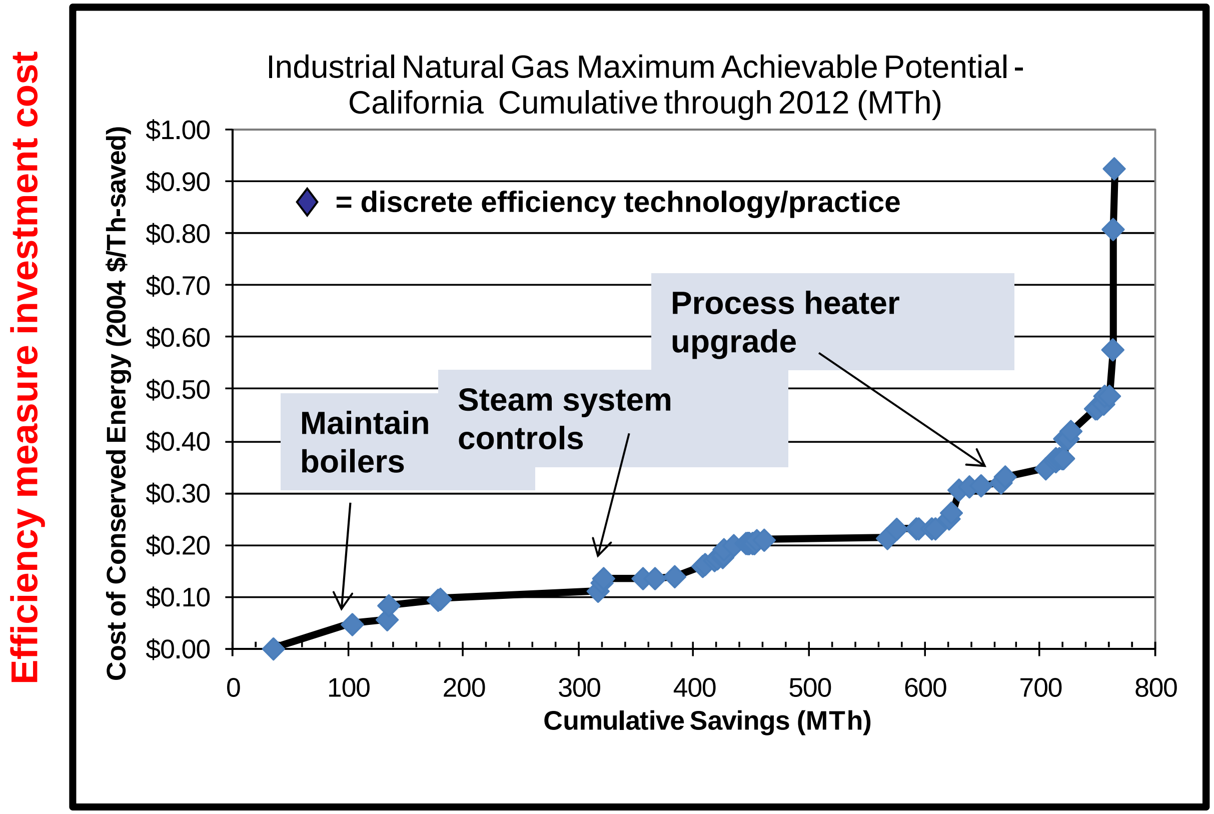


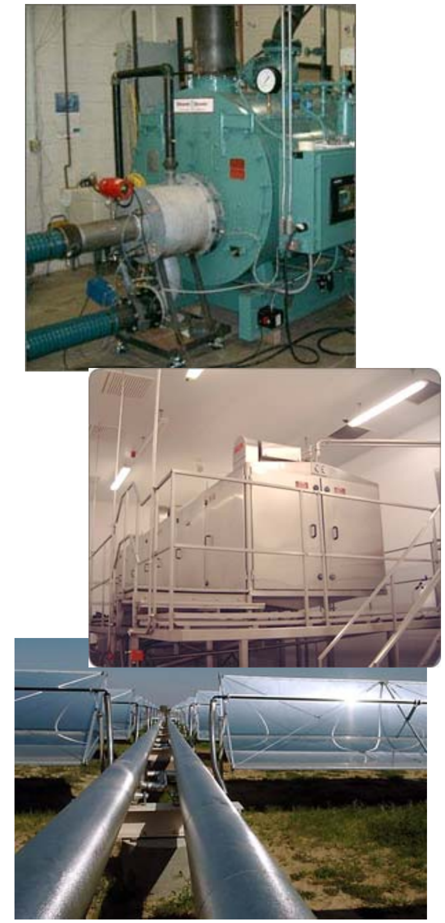
McCormick

Northwestern Engineering

Techno-Economic Potentials Analysis

Industrial Natural Gas Efficiency Example





Technical Potential of Efficient Measure = Base Case Equipment EUI × Applicability Factor × Not Complete Factor × Feasibility Factor × Savings Factor

Friedmann, R., F. Coito, E. Worrell, L. Price, E. Masanet, and M. Rufo (2005). "California Industrial Energy Efficiency Potential." Proceedings of the 2005 ACEEE Summer Study on Energy Efficiency in Industry, West Point, New York, ACEEE.

Hybrid Modeling Schematic

Black = Input-output model

Supply Chain Sectors

Producing Sector

Output (purchase) from IO sector i ($)

IO Analysis

2002 U.S. IO Total Requirements Matrix (426)

Input required from IO sector 1 ($)

…

Input required from IO sector n ($)

X

Environmental Coefficients for Supply Chain Sector n

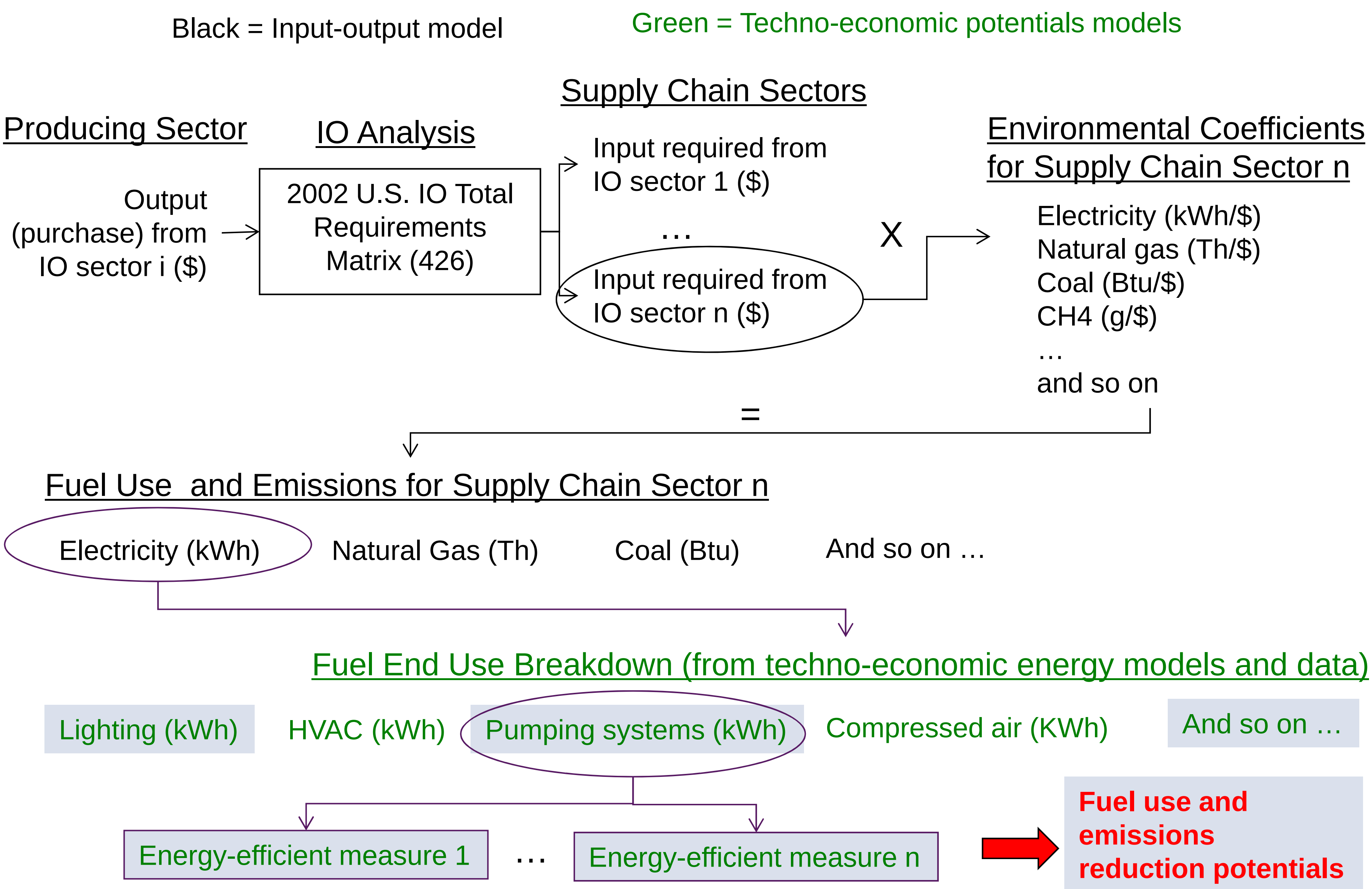
Electricity (kWh/$)
Natural gas (Th/$)
Coal (Btu/$)
CH4 (g/$)
…
and so on

=

Fuel Use and Emissions for Supply Chain Sector n

Electricity (kWh) Natural Gas (Th) Coal (Btu) And so on …

Hybrid Modeling Schematic



Manufacturer Leverage Characterization

Potential savings from efficiency upgrades

Fraction to plant's pumps, fans, drives, etc.

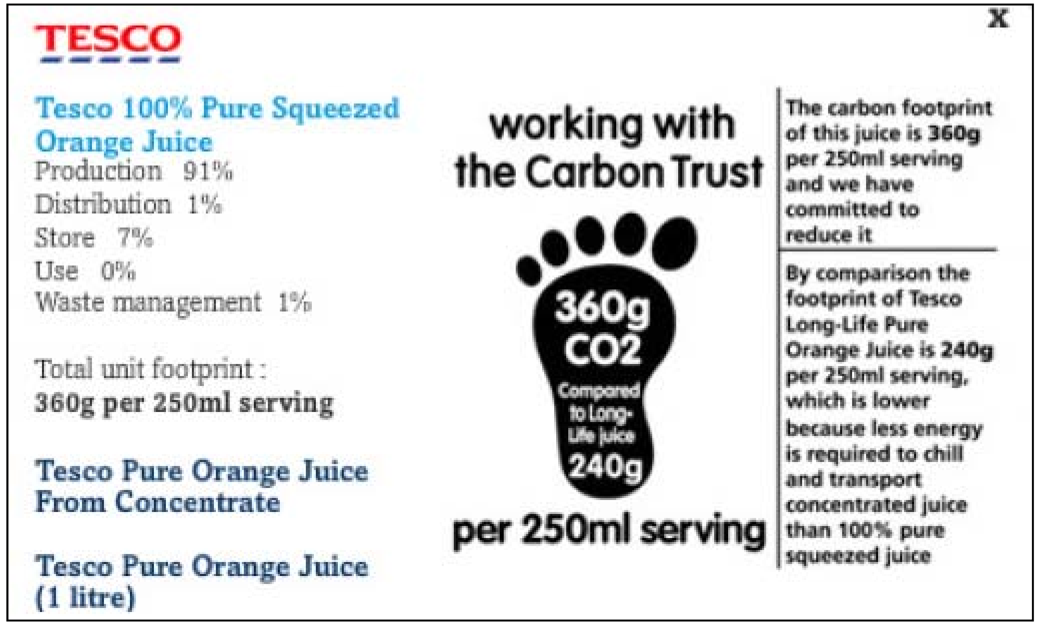
Auto plant electricity use

IO Sector	Description	Total Electricity Use (kWh)	Motor System Electricity Use (kWh)	Motor System Efficiency Potential	Potential Electricity Savings (kWh)
336110	Automobile and light truck manufacturing	727	313	15%	47
			Auto manufacturer total		***47***

An auto manufacturer might increase savings by a factor of 4 by replicating motor system efficiency best practices across just 10 key suppliers

Case Study:
If Carbon Labels Work, Which Products Should Be Labeled?

- Initiatives are emerging globally to estimate and report the carbon footprints associated with goods and services
  - Carbon Trust (UK) Carbon Reduction Label and British Standards Institute PAS 2050
  - Tesco (UK) and Wal-Mart (US) supply chain reporting initiatives
  - Industry-led initiatives (breweries, dairies, others)
  - California Assembly Bill 19
  - Waxman-Markey Bill
- Challenges
  - Cost, complexity, reliability
  - Data gaps and uncertainties
  - Singular focus on carbon
  - Market adoption
- Opportunities
  - Increased supply chain accountability
  - Improved energy and emissions management
  - Long-term corporate culture change toward continuous improvement



http://www.carbon-label.com/

Application to California Policy Analysis: Potential of Product Carbon Labels (for the California Air Resources Board)

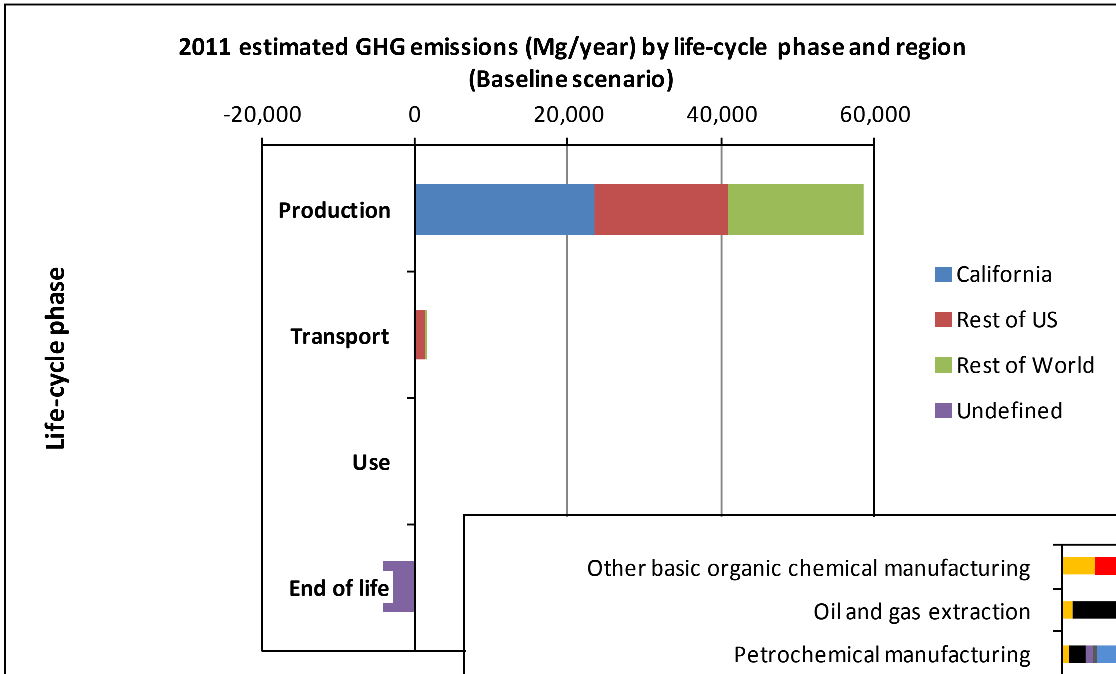
Research questions

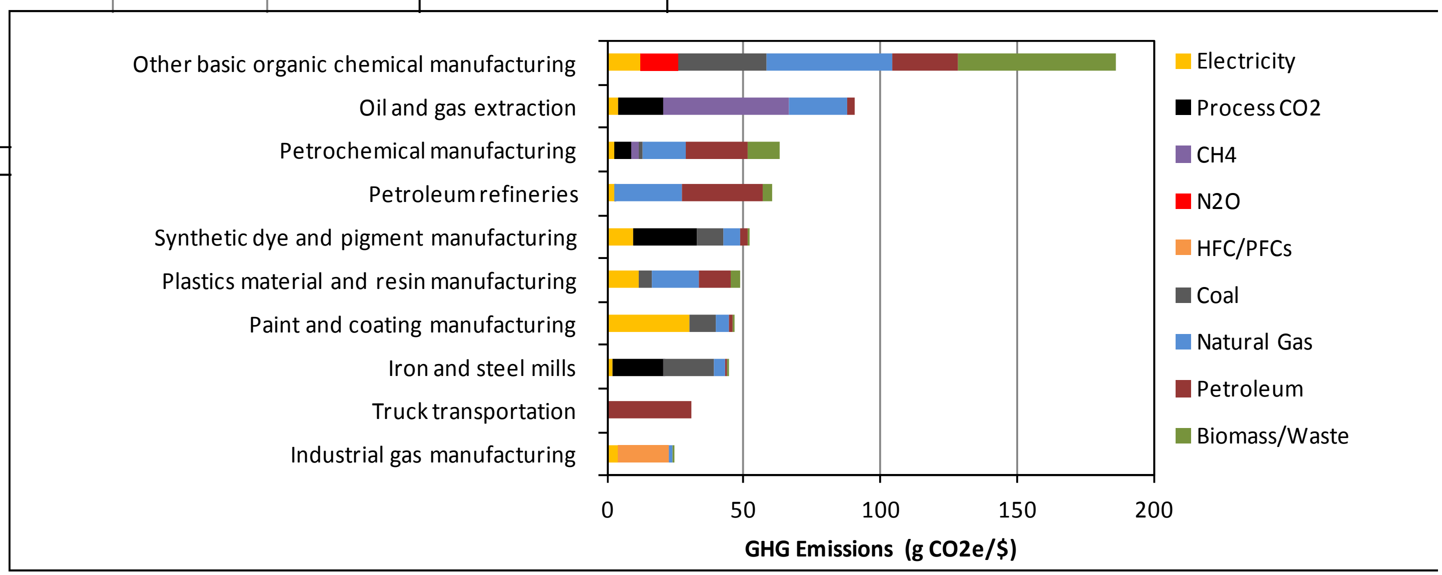
1. By how much might GHG emissions be reduced across the life-cycle of a given product if carbon labels and/or standards are successful in driving the market to best practice for low carbon and energy efficient life cycles?
2. Of the estimated emissions reductions, how much is likely to occur within California?

McCormick

Northwestern Engineering

Product analysis example: Paint



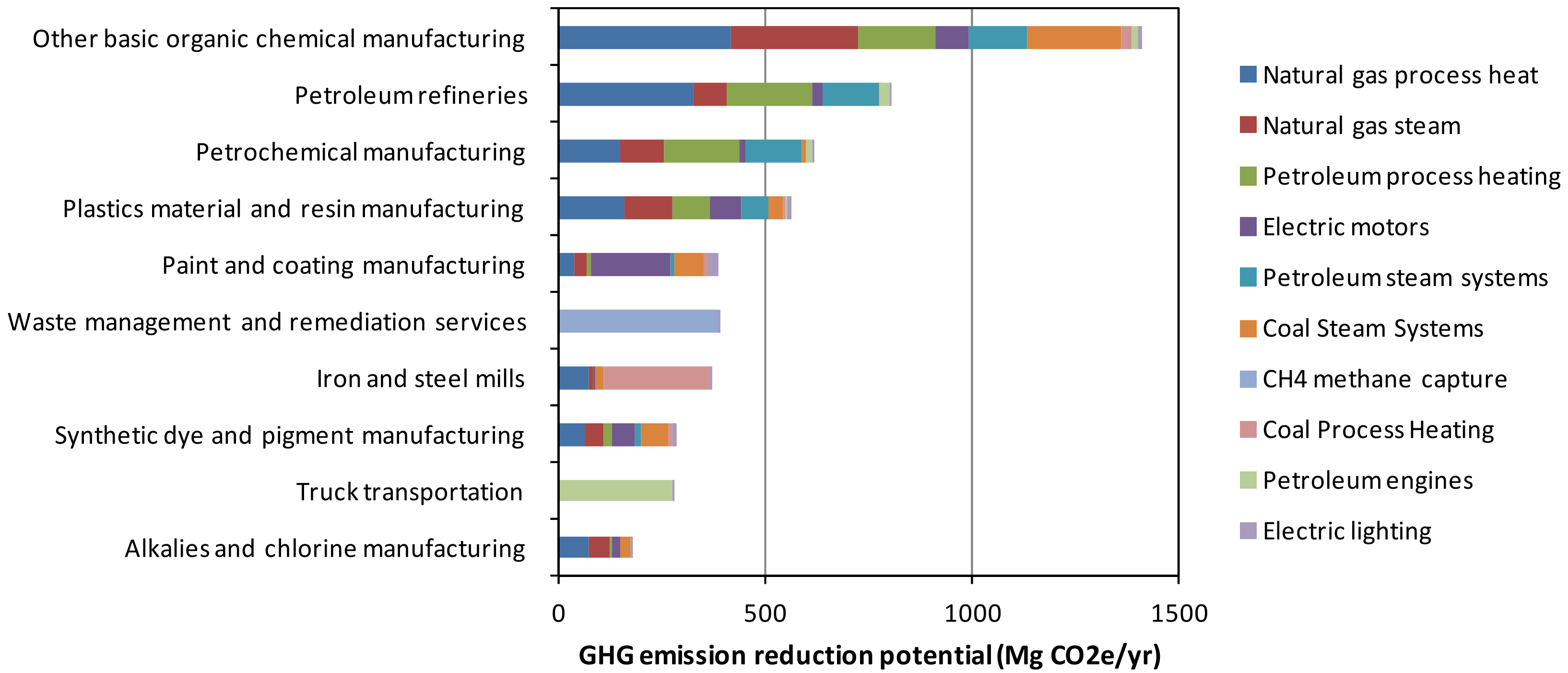


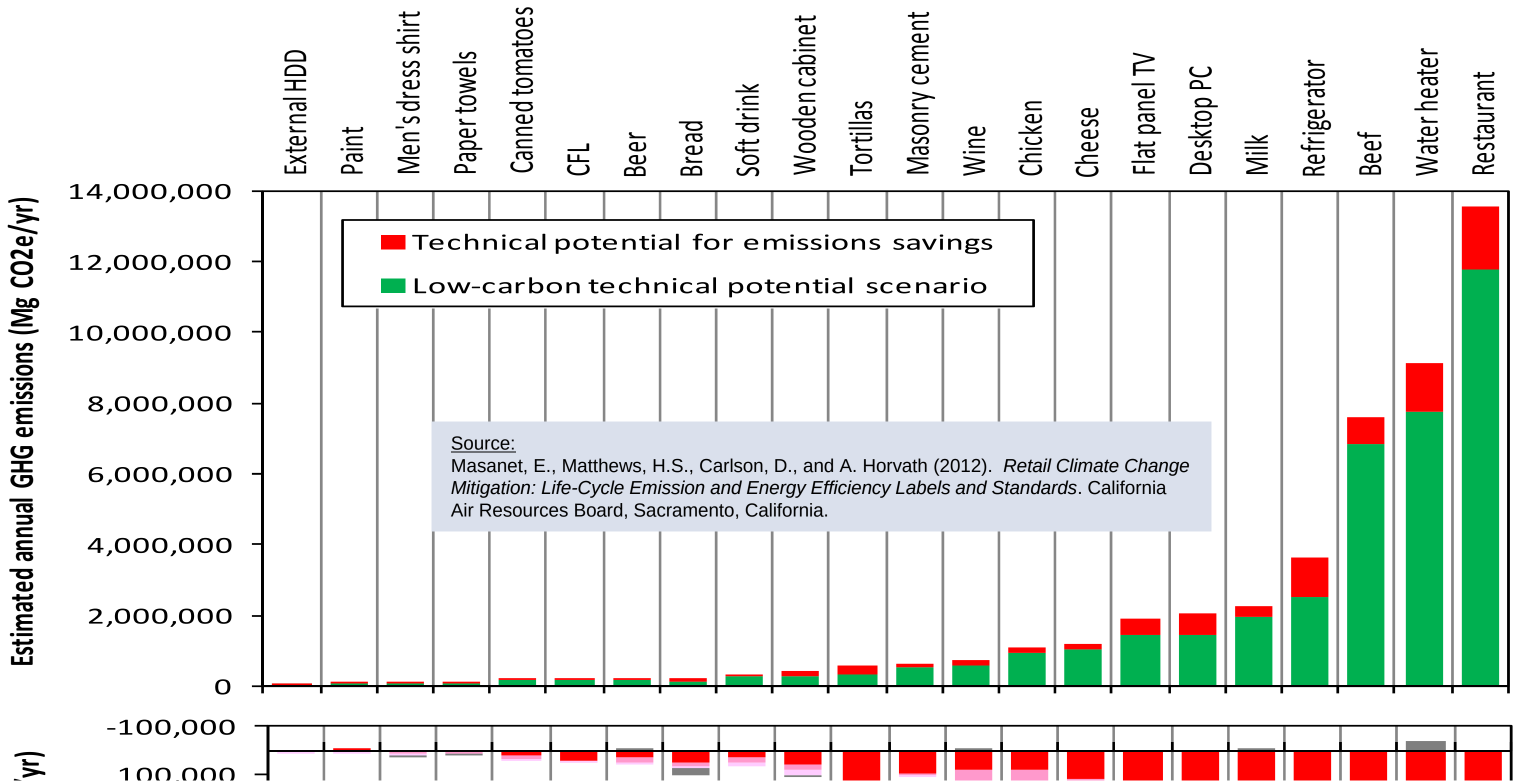
Top 10 sectors for supply chain GHG emissions

McCormick

Northwestern Engineering

Paint supply chain GHG emissions reductions opportunities (<3 year payback)





Policy-relevant insights

- Products must be selected strategically based on savings potential IN ADDITION TO total emissions footprints

- Much focus is on food, but greater savings may be achieved via appliances and services

- Methodology developed can help identify opportunities for large in-state savings; this enables strategic policy rather than inefficient and costly “blanket” approaches with questionable returns

McCormick

Northwestern Engineering

How Green is That Product? An Introduction to Life Cycle Assessment

- Nine-week MOOC (January – March, 2014)
- Goal: a basic quantitative introduction to LCA for scientists and engineers
- Topics:
  - Rationale for LCA
  - Quantitative basics (mass and energy balancing, scaling, unit process modeling)
  - Goal and scope definition
  - LCI and LCIA
  - Interpretation
  - ISO 14040 standards
  - Course project

coursera

Some statistics

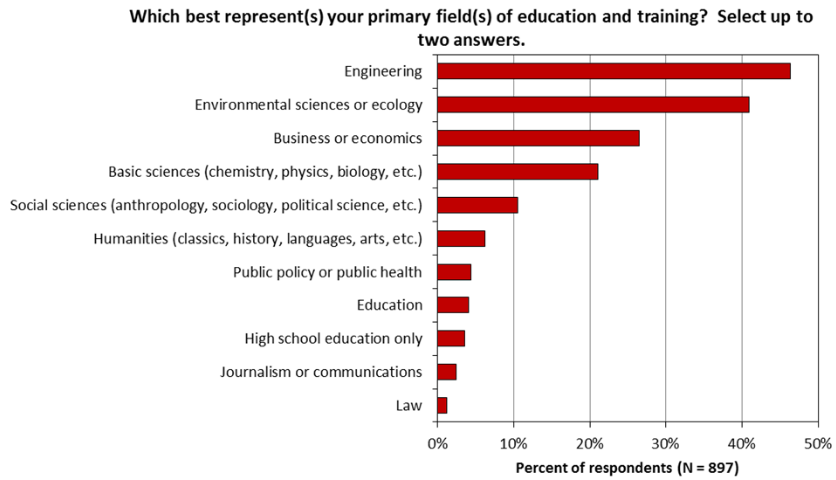
- Total student enrollments as of the course start date (Jan 25, 2014): around 17,000
- Students who watched all lecture videos: around 1,200
- Students who watched at least one lecture video: around 8,200
- Students who turned in one or more homework assignments: around 2,300
- Students who passed the course (final grade >=70%): around 700
- Students who passed the course with distinction (final grade >=90%): around 400
- Total discussion forum views: around 42,000
- Total discussion forum posts and comments: around 6,900

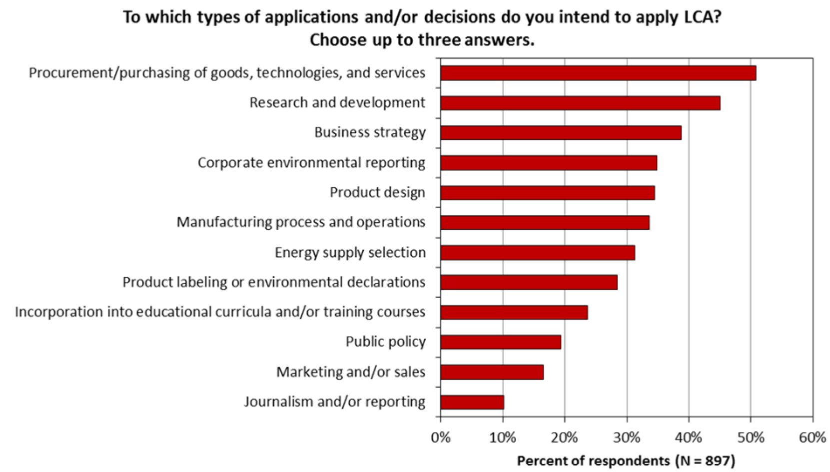
McCormick

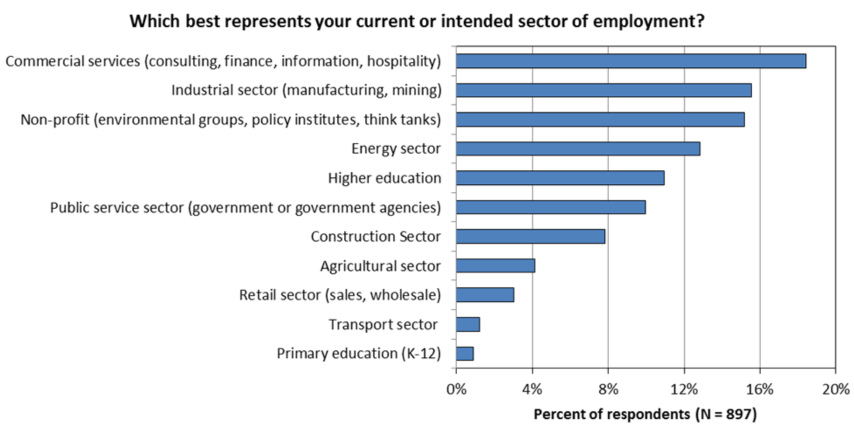
Northwestern Engineering

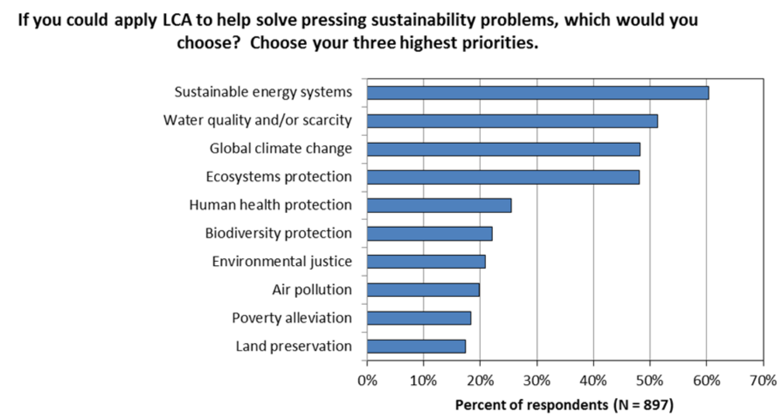
Advancing LCA pedagogy

Shifting needs of LCA students









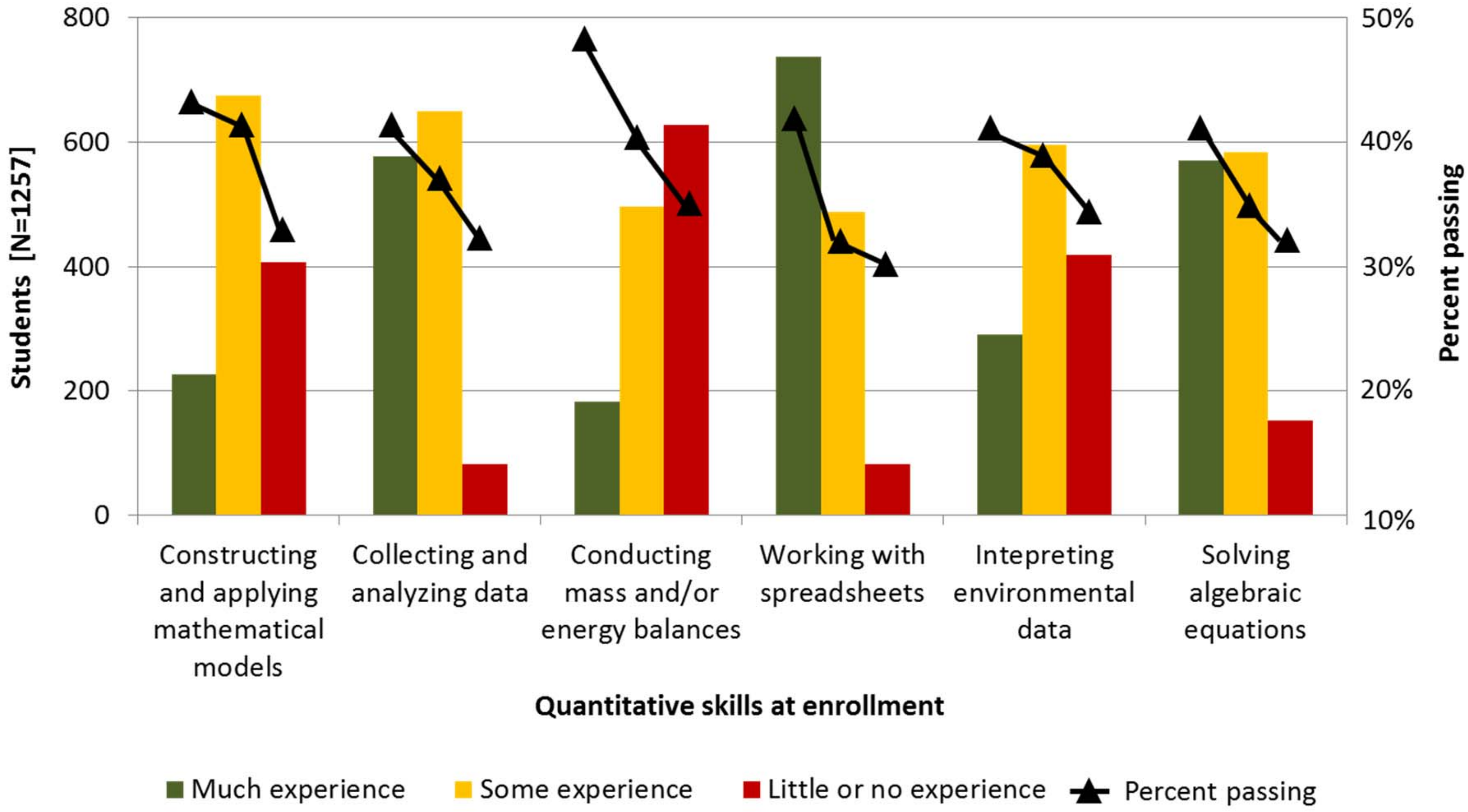
Masanet, E., and Y. Chang. (2014) “Who Cares About LCA? A Survey of 900 Prospective LCA Practitioners.” Journal of Industrial Ecology. In press.

McCormick

Northwestern Engineering

Advancing LCA pedagogy

Core skills and training



Masanet, E., Chang, Y., Yao, Y., Briam, R., and R. Huang (2014). "Reflections on a Massive Open Online LCA Course." International Journal of Life Cycle Assessment. In press.

McCormick

Northwestern Engineering

Acknowledgements

Undergraduate students (20): Kristin Bernstein (2013), Cindy Chen (2014), Kedric Daly (2014), Sarah DeSoto (2013), Michael Goldberg (2013), Asher Goldman (2013), Abby Hawley (2013), Jan Jaro (2013), Jeremy Koszela (2012), Callie Larson (2013), Lauren Miller (2012), Eric Niemeyer (2013), Nirajan Rajkarnikar (2012), Arun Ramachandran (2012), Brooke Stanislawski (2013), Christopher Timpone (2012), Paige VonAchen (2012), Randall Waymire (2014), Sarah Wolff (2013), Lily Zhou (2014)

M.S. students (16): Craig Arnold (M.S. 2012 – currently at Apple), Bisola Bruno (current), Xinyi Che (current), Nuoa Lei (current), Do Yong Lee (M.S. 2014), Gonzalo Lema (M.S. 2014 – currently at SUMAC), Jiaqi Liang (M.S. 2014 – currently at CLEAResult), Liying Li (current), Shiqi Louhong (M.S. 2014 – currently at General Motors), Zhen Lv (M.S. 2012), Sam Malin (M.S. 2012 – currently at Invenergy), Matthew Montalbano (M.S. 2014), Fred Thwaites (M.S. 2012 – currently at CLEAResult), Hui Yao (M.S. 2014 – currently at General Motors), Benjamin Walker (M.S. 2014 – currently at Hospital Energy), Yiqi Zhang (current).

Ph.D. students (3): Remy Briam (current), Runze Huang (current), Yuan Yao (current)

Postdoctoral Scholars (3): Yuan Chang (2012-2014 – currently Associate Professor at Central University of Finance and Economics, Beijing), Venkata Krishna Kumar Upadhyayula (2012-2013 – currently Life Cycle Analyst at SABIC), Michael Walker (2012-2014 – currently Instructor at University of Colorado, Boulder)

Thank you for your attention!

Questions?