Sustainable Manufacturing: Opportunities, Trends, and Technoeconomic Analysis

AMO Strategic Analysis (StA) Team

Poster Presenter:
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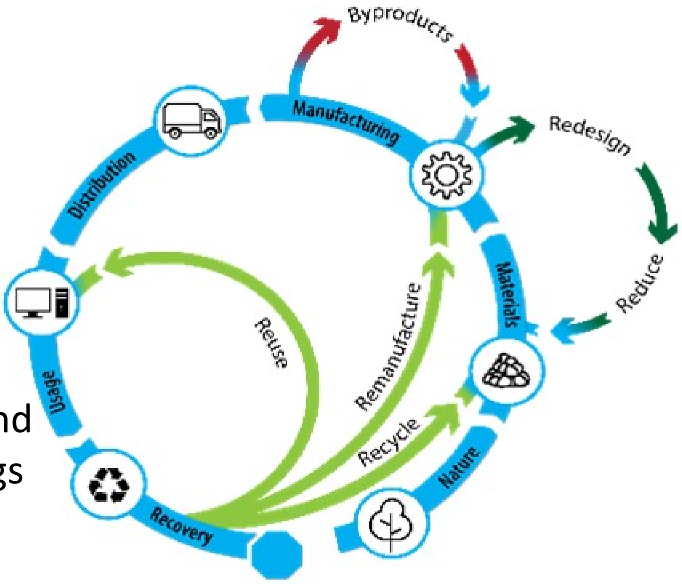
This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

- The multi-laboratory (Argonne National Laboratory, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, and Oak Ridge National Laboratory) AMO Strategic Analysis (StA) Team provides independent, objective, and credible information to inform decision-making.
- The StA team submitted 6 total posters for this year's Program Review; the research topics are ongoing and do not follow the typical poster format
- This poster, **"Sustainable Manufacturing: Opportunities, Trends, and Technoeconomic Analysis"** includes information on three projects:
  1. Electrotechnologies for Process Heating
  2. Early Assessments of Emerging Technology Assessment
  3. Industrial Sector Trend Analysis: Global Industrial Decarbonization/ value of energy efficiency

Project Objective(s) – Sustainable Manufacturing

- **Sustainable manufacturing:** encompasses a widening range systems issues (e.g., energy intensity, carbon intensity, and use intensity) and solution can enable a more efficient and competitive advanced U.S. manufacturing future.
- **Challenge with many traditional manufacturing systems**: Develop an inefficient linear model, starting with raw materials extract (mining) and end disposal in a landfill at the end of the product's useful life.
- **Circular economy** (represented by the figure to the right) redirects the current approach by providing opportunities to re-manufacture and reuse end-of-life consumer products, leading to more efficient use of materials.
- **Analyzing the supply chain and material flows: throughout the product's entire lifecycle:** Can help to identify energy, material, and water savings opportunities for greater U.S. economy (including the production and delivery of energy and energy use within the industrial, transportation, and buildings sectors)



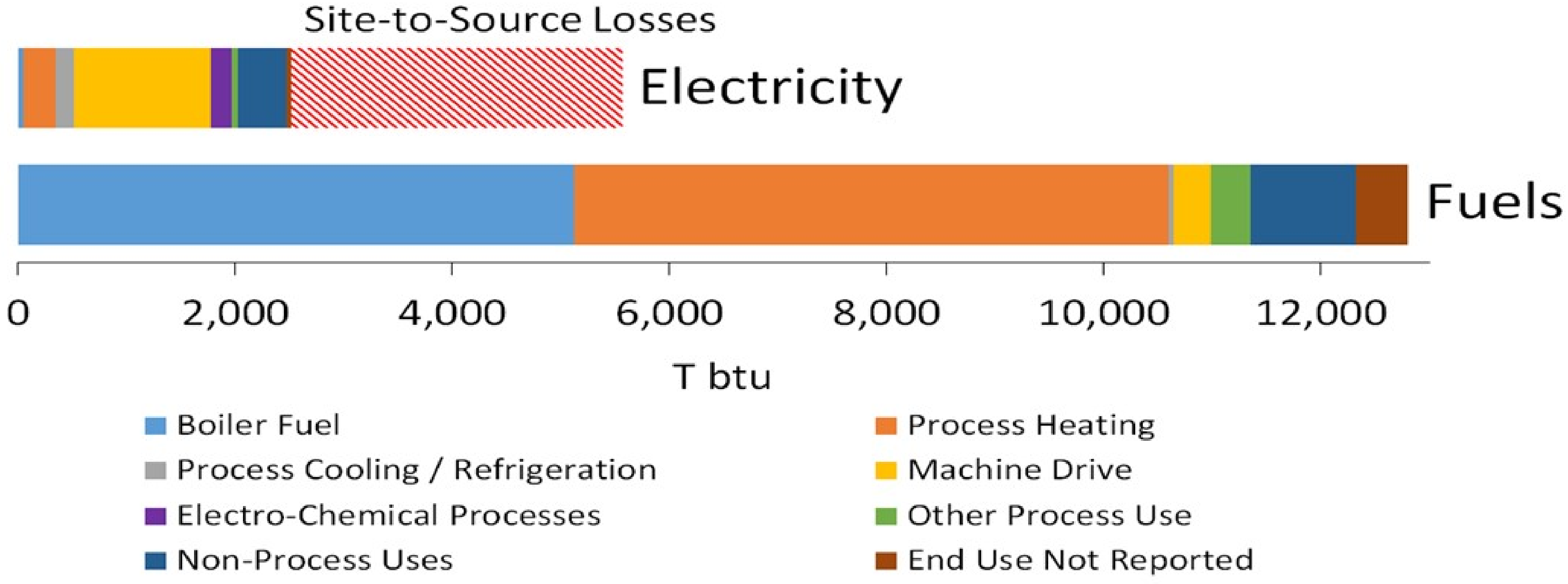
- The team's **past and current sustainable manufacturing activities** include: developing baseline knowledge, analyzing long-term trends, and assessing current opportunities. Methods, data, and results are vetted through conference presentations, workshop collaborations, and reports.
- A key in doing so is addressing the challenge of how to evaluate different strategies' potential by developing general evaluation approaches and establishing a baseline to use a reference point.

Electrotechnologies for Process Heating

- Project Overview
  - Starting point for the study
  - The two analysis approaches and their scope
- Industry Focused approach
  - Methodology and steps
  - Results from the different industries
- Technology Focused approach
  - Methodology and steps
  - Framework to use Lifecycle Industry GHgas, Technology and Energy through the Use Phase (LIGHTEnUp) modeling to find impact of ET
  - Results from the application of the LIGHTEnUp framework to cement sintering
  - Analysis of carbon emission impact
  - Sensitivity analysis with different grid mix

Application of Electrotechnologies in Industrial Process Heating Systems

- 2016: direct fuel combustion accounted for 73% of global industry energy use, while electricity accounted for only 27% (International Energy Agency 2018c).
- Fuels combusted in industrial facilities are primarily used for process heating (46%) and for fueling boilers (41%), with the remainder powering motor-driven systems and other end uses.
- Figure below show the relative impact for various industrial processes



Distribution of energy end-uses in the U.S. manufacturing sector in 2014. The top bar shows end uses of electricity (including site-to-source losses) and the bottom bar shows direct combustible fuel use. (U.S. Energy Information Administration 2014)

Electrotechnologies for Process Heating

Starting Point A need to account for characteristics of electric heating processes, identify barriers to its implementation and determine its potential impact on US energy consumption.

Industry Focused Analysis: An analysis of all process heating applications in major industries to identify opportunities for electrification.

- Involves understanding the industry landscape and determining the potential impact of electrification in the sector.

Technology Focused Analysis: An analysis of specific ETs to understand its capability, barriers and potential in replacing traditional processes.

- Involves studying the fundamental energy-material interaction of the ET to understand its capability in processing different materials.

The two approaches are co-dependent and together help achieve the study's goal

Process	Energy Intensity (MMBtu/ton)	Process Requirement	Electrotechnology Options
Ironmaking			
Blast Furnace	11.72	Reduction of iron ore into iron using coke and hot air blast. Sometime supplemented by gaseous fuel.	Option is to eliminate use of coke through use of EAF steel making process.
Direct Reduction - current in USA	9.17	Reduction of iron ore by using reducing gases or other materials at 850 deg. C. There is very little external energy used other than the hot reducing gases/agents as reducing agent.	No good available option to produce reducing agent.
Steelmaking			
Basic Oxygen Furnace	0.58	Minimum external fuel used. The feed material is pig iron and other material added in BOF.	Electric heating in EAF to substitute BOF steel production.
Electric Arc Furnaces	1.86	Use of electricity and fuel. Electricity 1.42 MMBtu/ton, fuel 0.44 MM Btu/ton.	Plasma technology to replace fuel firing and achieve charge preheating
Rolling (Integrated and Mini Mills)			
Hot	2.58	Heating of steel shapes to up to 2300 deg. F. mostly by using natural gas fuel.	Induction heating for continuous systems and resistance or some batch systems.

Table 1: Initial Analysis for Iron and Steel Industry where the different process heating steps are studies, its energy intensities determined and alternative electrotechnologies are identified

Industry Based Analysis - Steps

Step 1 - Identify major manufacturing steps or processes.

Step 2 - Collect energy use data for the selected processes

Step 3 - Identify applicable ETs which meet the process requirements

Step 4 - Find impact to energy consumption assuming large scale electrification based on considerations for thermal efficiency and other factors. (Technical Potential)

Case	Description	Total On-site (TBtu/ year)	Total Primary (TBtu/ year)	Incremental Electricity On-site (TBtu/year)	Incremental Energy use at generation (TBtu/year)
	Baseline – Current Usage	860	1,174	-	-
1	Convert to Direct Reduced Iron (DRI) based EAF steel making process	1,028	1,750	277	839
2	Convert to Electrowinning iron production with EAF steel making	945	2,836	847	2,567

Table 2: Results from the Analysis of Iron and Steel Sector. Case 1 represents a scenario where all integrated steel mill operations are converted to mini mills by the increased use of Direct Reduced Iron. Case 2 is a scenario for converting traditional steel making processes to electrowinning, an Electrolysis based steel making process proposed by Boyan Yuan.

Electrotechnologies for Process Heating

Technology Based Analysis - Steps

Step 1- Study microwave heating mechanisms

Step 2 - Review Applications in Industry

Step 3 - Develop case studies for specific applications using LIGHTEnUp tool

Step 4 - Expand the model to determine the application in a subsectors

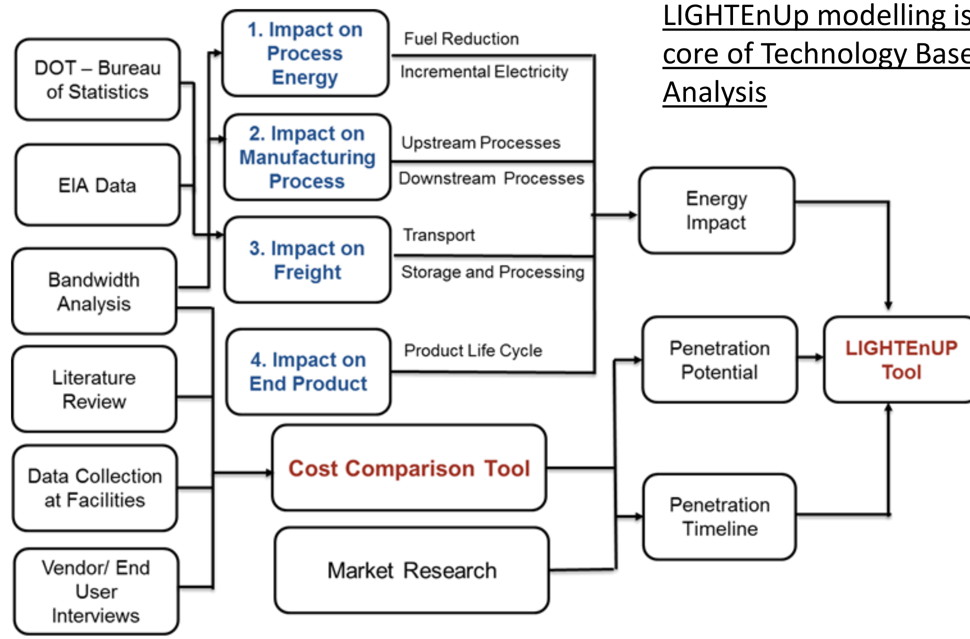


Figure 1: Process Flow of LIGHTEnUp modelling.

LIGHTEnUp modelling is in the core of Technology Based Analysis

LIGHTEnUp Analysis - Components

1. Impact on Process Energy Impact
2. Impact on Manufacturing Process
3. Impact on Freight
4. Impact on End product

LIGHTEnUp Results

Pictures to the right show the preliminary results from the case study of deploying microwave assisted sintering of cement

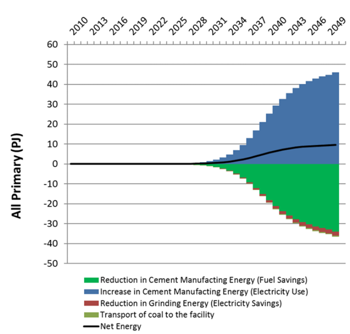


Figure 2: Effect to the primary energy with 10% deployment of microwave sintering

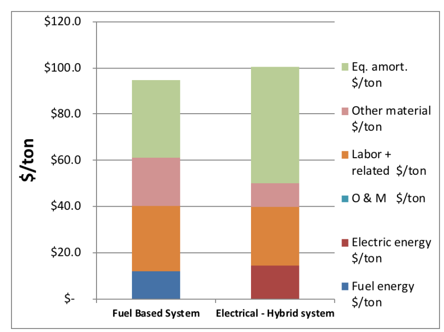


Figure 3:Holistic Cost comparison model of microwave sintering vs traditional sintering

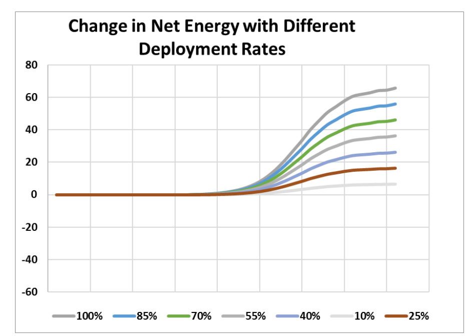


Figure 4: Effect on the primary energy with different rates of deployment of microwave sintering technology

Analysis of emerging technologies Conference Special Sessions

LCA Conference Special Sessions on Emerging Technologies:

American Center for Life Cycle Assessment ACLCA

- "Life Cycle Energy Analytical Framework for Advanced Manufacturing – an Efficient Materials and Industry Energies Future", San Francisco, CA, October 6-8, 2014
- "Cultivating uniform methods for prospective LCA of emerging technologies – A Round Table Discussion" Vancouver B.C., Canada, October 6-8, 2015
- "Developing Robust Methods for Prospective LCA for Early Stage Technologies (Part 1 and 2)." Life Cycle Assessment XVI, Charleston, SC, September 27-29, 2016.
- "Towards a framework for LCA of emerging technologies", Life Cycle Assessment XVII, October 2 - 5, 2017, Portsmouth, NH, USA
- "Case Studies on the Prospective Analysis of Emerging Technologies", Life Cycle Assessment XVII, October 2 - 5, 2017, Portsmouth, NH, USA
- "LCA of Emerging Technologies: Open Discussion of Analysis Framework Developments", Life Cycle Assessment XVII, September 25th-27th, 2018, Fort Collins Marriott, Fort Collins, CO, USA

ISSST:

- "The Intersection of Life Cycle Assessment and Techno-Economic Analysis of Emerging Technologies", ISSST 2018, June 26th-28th, 2018, Henry Hotel, Buffalo NY
- "Life Cycle Assessment of Emerging Technologies: The case for a sub-discipline research network", ISSST 2018, June 26th-28th, 2018, Henry Hotel, Buffalo NY

Analysis of emerging technologies

Journal of Industrial Ecology, Special Issue on Life Cycle Analysis of Emerging Technologies

"Life Cycle Assessment of Emerging Technologies: Discussion of Evaluation Techniques at Different Stages of Market and Technical Maturity", Journal of Industrial Ecology, Special Issue on Life Cycle Analysis of Emerging Technologies, in-submission

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Early assessments of Emerging Technologies:

- Provide greatest opportunity to influence design and ultimately environmental performance,
- Least available data, greatest uncertainty, and a paucity of analytic tools available for addressing these challenges
- Fundamental assessment approach is akin to that of existing technologies yet emerging technologies pose additional challenges.

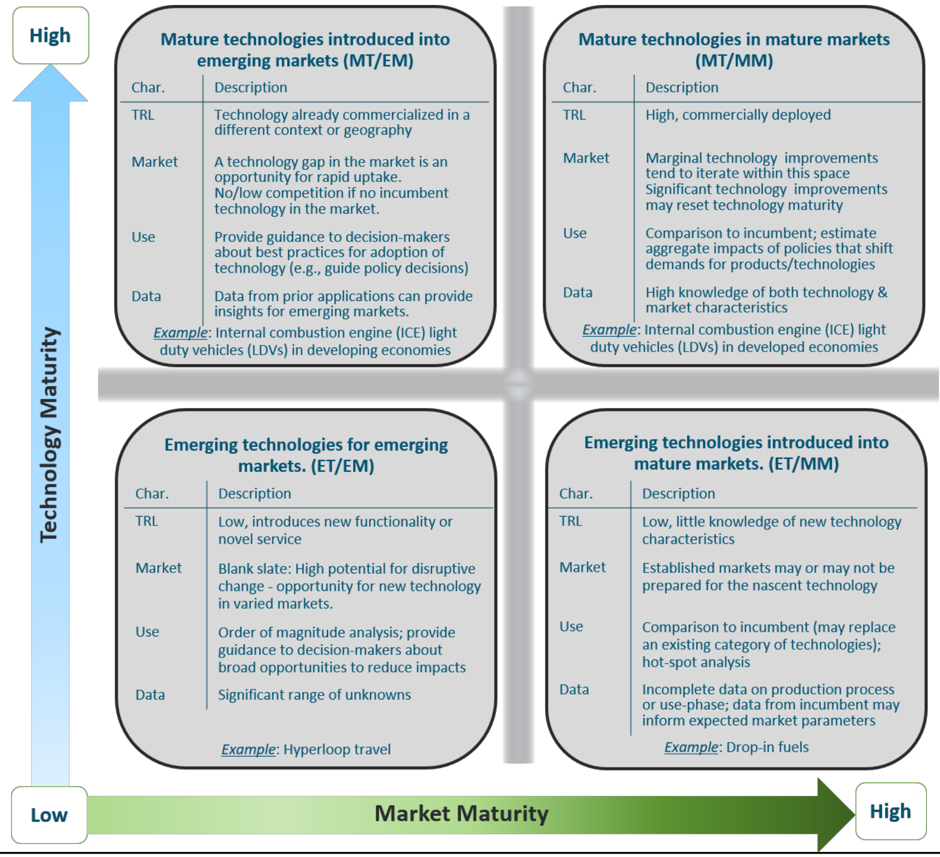
This paper presents:

- A broad set of market and technology characteristics that typically influence an assessment of emerging technologies
- Identify questions that researchers must address to account for the most important aspects of the systems they are studying.
  - 1) Guidance to identify the specific technology characteristics and dynamic market context that are most relevant and unique to a particular study;
  - 2) An overview of the challenges faced by early stage assessments that are unique because of these conditions;
  - 3) Questions that researchers should ask themselves for such a study to be conducted;
  - 4) Illustrative examples from the transportation sector to demonstrate the factors to consider when conducting LCAs of these technologies.

The paper is intended to be used as an organizing platform to synthesize existing methods, procedures and insights and guide researchers, analysts and technology developer to better recognize key study design elements and to manage expectations of study outcomes.

Analysis of emerging technologies

Journal of Industrial Ecology, Special Issue on Life Cycle Analysis of Emerging Technologies



Quadrants lead to specific questions that affect choices at the goal and scope definition stage as well as selection of methods to employ in analysis.

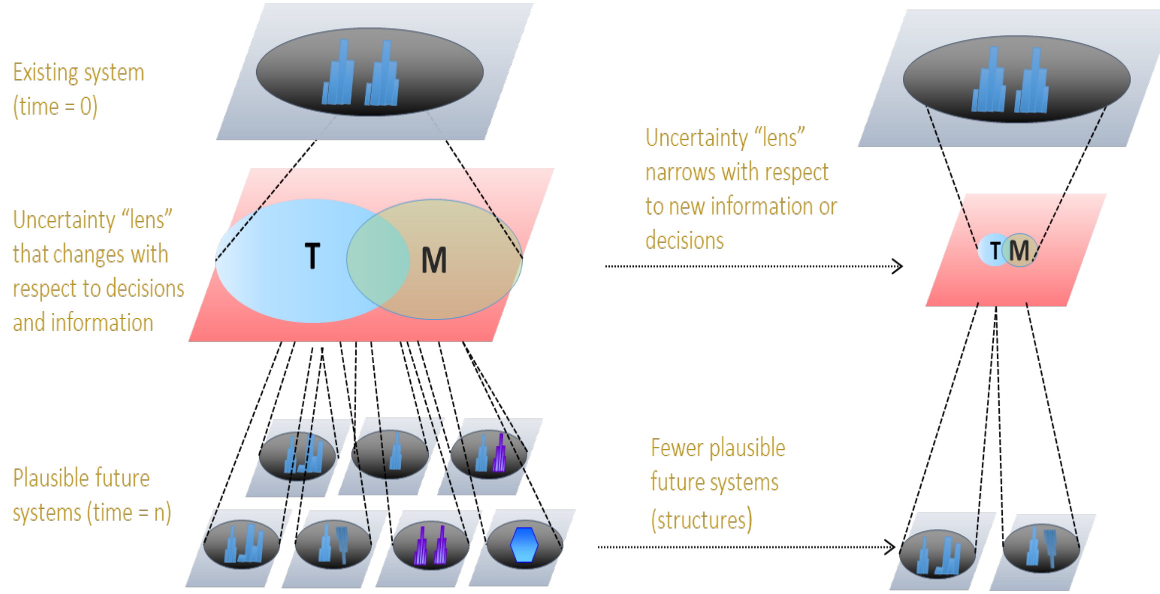
Use = common types of decisions being informed using LCA; other uses may still be applicable.

Technology and market maturity quadrants: figure purpose is to help an analyst situate themselves in a quadrant that will then lead to posing specific questions that affect choices at the goal and scope definition stage & selection of methods to employ in their study. Inside the quadrants are descriptions of the characteristics (char.) that would help an analyst fit their study into a quadrant.

† Journal of Industrial Ecology, Special Issue on Life Cycle Analysis of Emerging Technologies (In Review)
Joule Bergerson, Adam Brandt, Joe Cresko, Michael Carbajales-Dale, Heather L. MacLean, H. Scott Matthews, Sean McCoy, Marcelle McManus, Shelie Miller, William R. Morrow III, I. Daniel Posen, Thomas Seager, Timothy Skone, Sylvia Sleep

Early Assessments of Emerging Technologies
Accounting for uncertainty

- **<u>Structure:</u>** set of parameters that affect the environmental impacts of technology (independent of design and deployment). Examples include installed infrastructure, intensity of the electricity grid, and the regulatory environment.
- **<u>System:</u>** where the impact of a technology in a market occurs & where the effects of technology/market uptake are observed. Inclusive of all elements within the system boundaries of the analysis. technology and market bubbles are embedded in a wider structural bubble (*e.g., see pink rectangle*), calling attention to where exactly changes are taking place.



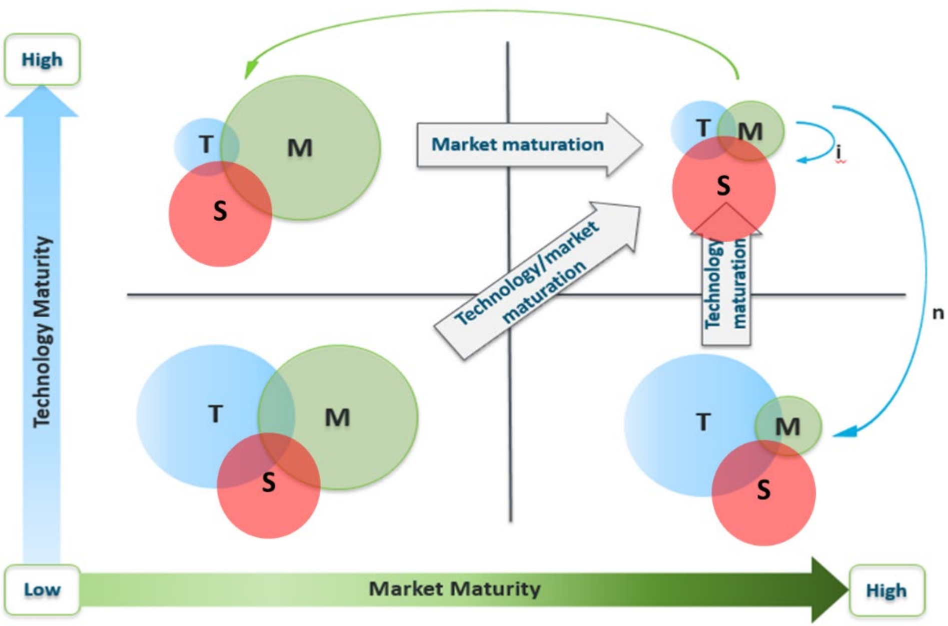
- **<u>Accounting for uncertainty is critical in LCAs</u>**
Step 1: Identifying the parameters that may have the greatest influence on future environmental impacts when the technology is at full-scale

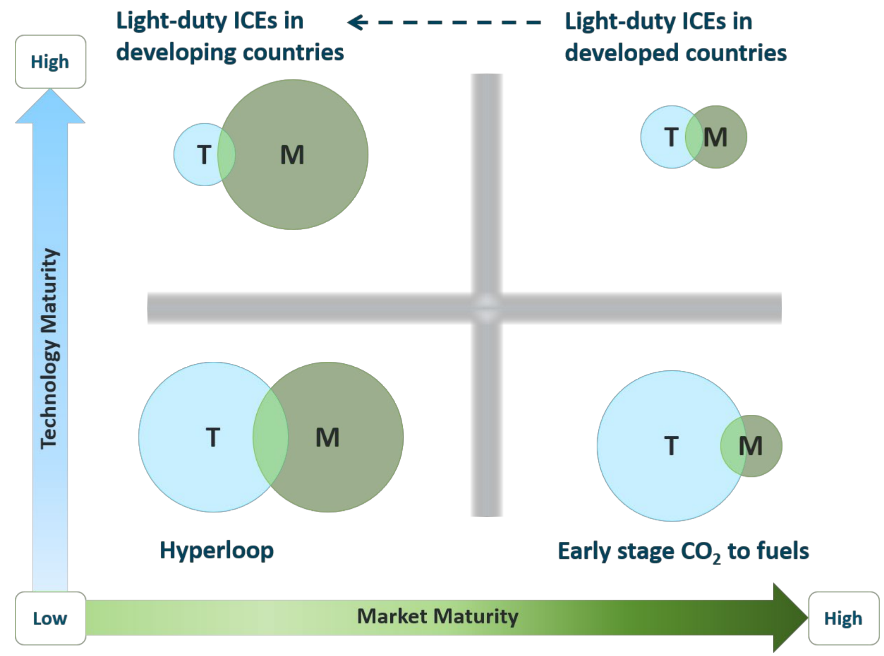
  Step 2: Focus LCA data collection efforts to A) reduce uncertainty around those parameters, B) enable early design decisions

- Both technical and market maturity uncertainty occur within the overall system and are interdependent.
- There can be significant overlap between factors that contribute to both technological and market uncertainty
  - User behavior will impact technological design and vice versa
- The technology factors that tend not to overlap with market are often associated with material extraction and manufacturing phases of a product life cycle.

Analysis of emerging technologies

Journal of Industrial Ecology, Special Issue on Life Cycle Analysis of Emerging Technologies





- Relative magnitudes of uncertainties associated with technology and market maturation and changes in uncertainty as technologies move between quadrants
- For example, light-duty vehicles (e.g., a Ford F150 pickup truck) are a mature technology in a mature market but are continually incrementally improved (e.g., material changes to individual technologies that increase energy efficiency by a few percentage points) (top right)
- As established light-duty ICEs are deployed in new markets the market uncertainty grows even though the technology is mature. (top left)
- Potentially disruptive technologies where very little is known about the technology and market starts with high degrees of uncertainty on both axes, such as Hyperloop technology. (bottom right)

Early Assessments of Emerging Technologies: Technology Factors

Technology factors
• Interaction with technological system • Does the innovation fit within an existing technological system (e.g., a new part), or is it an entirely new system? • Does it require/allow changes to the rest of the system (e.g., vehicle light weighting allows for powertrain resizing) • Is the technology standalone or does it require changes to background infrastructure (e.g., electric vehicle changing infrastructure)? --> See additional 'market' questions • Functional materials (e.g., rare-earth metals for EV batteries) • Are there resource criticality impacts or supply limitations? • What are the supply chains and LCA impacts associated with these materials? • Do novel materials (e.g., nanometals) introduce new environmental concerns, and how might these be quantified? • Commercialization pathway • What are current commercial or lab scale material and energy requirements? • What scale is considered and what scaling rules apply (e.g., improved heat transfer at scale for a chemical process)? • What future process efficiency improvements can be expected? Over what time horizon? • Are there thermodynamic limits to process improvement? • Production and use characteristics • The product's functional unit(s)? • Underlying manufacturing technology (e.g., thermochemical vs biochemical routes)? • Facility design (e.g., purpose-built vs assembly line; batch vs flow reactor)? • What are the direct process emissions and production process inputs (e.g., energy needs)? • What is the expected efficiency and/or emissions in use phase? • Expected product lifetime? • What co-products are produced? • Other characteristics that affect end use (e.g., electric vehicle range and charging time)?

Early Assessments of Emerging Technologies: Market Factors

Market factors
Service offered by the technology • Does the technology offer a new service or change to existing services? • For general use technologies (e.g., internet), what use cases are considered (e.g., entertainment? online commerce? telecommunication?) Background systems • Policies and regulations? • Characteristics of supporting infrastructure (e.g., Emission intensity of the average or marginal electric grid, existing road networks, fuel distribution systems, etc.)? Consumer behavior • How will the technology be used (e.g., will autonomous vehicles be shared, or individually owned?) • How will the technology affect existing consumption patterns (e.g., direct rebound effect (Sorrell et al. 2009), mix of products consumed, characteristics of those products)? • What incumbent product (if any) will be displaced? • What supporting technologies may be encouraged/enabled? • User interactions? Market dynamics • Indirect rebound effects (e.g., income rebound, indirect fuel use effect) and other market-mediated effects (e.g., indirect land use change, learning-by-doing, spillover effects to other regions or technologies)? Adoption patterns and characteristics of adoption regions: • Speed of adoption, diffusion effects? • Location of potentially impacted systems (e.g., is there a sensitive ecosystem nearby? is there a large population center that will experience changes in air quality)? • Heterogeneity of local background systems? • Local climate? • Cultural and social preferences affecting adoption patterns and use? Internal consistency • What is the time frame and geography of analysis? • Is evolution of background and foreground systems consistent (e.g., greening of electric grid alongside improvement of the technology within future scenarios)? • Does the background system respond to the rollout of the technology (e.g., do electric vehicles play a role in grid storage? Is additional electricity demand accounted for?)

Industrial Sector Trend Analysis: Global Industrial Decarbonization

Workshop "*Technologies and Policies to Decarbonize the Industrial Sector*"

Aspen Global Change Institute Workshop, November 11-16, 2018 Aspen

Background:

- Identifying the most promising technologies and politically-implementable, effective policies to decarbonize the industry sector requires cross-disciplinary expertise.
- To map a way forward, the Aspen Global Change Institute (AGCI) and three co-chairs assembled a group of 28 experts in various industries, policy design, and sociological considerations of equity and global development.
- A week-long workshop was held in Aspen, Colorado. The workshop included presentations by every expert, discussions, break-out groups, and an end-of-workshop survey.
- Draft Report is in development

Attendee Affiliations

- Resources for the Future
- Department of Energy
- Breakthrough Energy Ventures
- Hewlett Foundation
- Siemens
- American Council for an Energy-Efficient Economy
- Imperial College London
- CDP
- Energy Foundation China
- Yale University
- Bellona Europa
- Shell International Ltd.
- BASF
- Children's Investment Fund Foundation
- Lawrence Berkeley National Laboratory
- Northwestern University
- Energy Innovation
- Jadavpur University, Kolkata
- The Energy and Resources Institute
- Energy Project Investment Consulting LLC
- University of Maryland
- BlueGreen Alliance
- Energy Research Institute

Industrial Sector Trend Analysis:

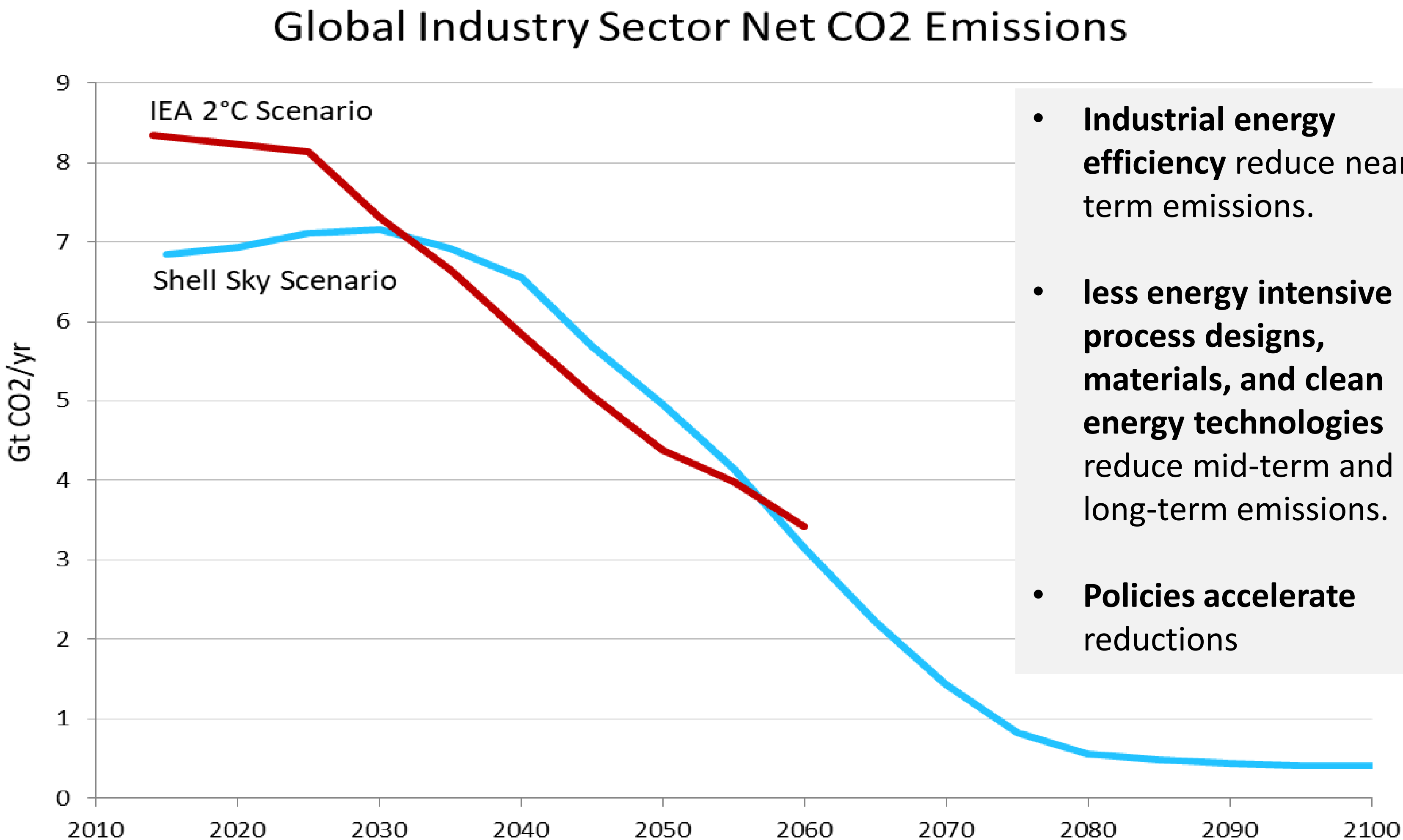
Technologies and Policies to Decarbonize the Industrial Sector – Workshop Report

- Anticipated Industrial Decarbonization Time-Frame
- The global industrial sector represents a diverse set of interrelated industries with a stock of some 2000+ cement plants, 500+ blast furnaces, and thousands of chemical, aluminum, paper, glass, ceramic, and other industrial facilities; often with specific process, material, and energy requirements.

Timeframe	Actions	Emissions Reductions
2020-2035	Efficiency improves continuously, with most industrial processes undergoing incremental improvements. After 2030, diminishing returns mean that reductions taper off. Some processes shift towards electricity, particularly for light industry, where electricity use doubles from 2020 to 2040.	Some 20% reduction from current practice, but this is largely offset by demand growth.
2035-2050	Structural shifts start to emerge, but they are based on technologies that are available and nearing maturity for commercial deployment in the 2020-2035 timeframe. CCS falls into this category and deploys rapidly through this period, assuming a market pull or price push to incentivize it.	A further 30% reduction from current practice, i.e. a 50% reduction in total.
2050-2070	A further structural shift emerges based on process and energy technologies that are nascent today but develop rapidly from pilot plant to demonstration plant in the period 2020-2050. These technologies will be ready for large-scale deployment thereafter. Hydrogen in heavy industry scales rapidly during this period. Given sufficient policy push, this period could deliver net-zero emissions for industry.	A further 30-50% reduction, potentially delivering net-zero emissions.
2070-2120	The long (and possibly fat) tail of fossil fuel use in industry shrinks, with a non-fossil, zero-emission industrial sector eventually emerging.	100% reduction in emissions and little remaining use of CCS.

Industrial Sector Trend Analysis:

Technologies and Policies to Decarbonize the Industrial Sector – Workshop Report



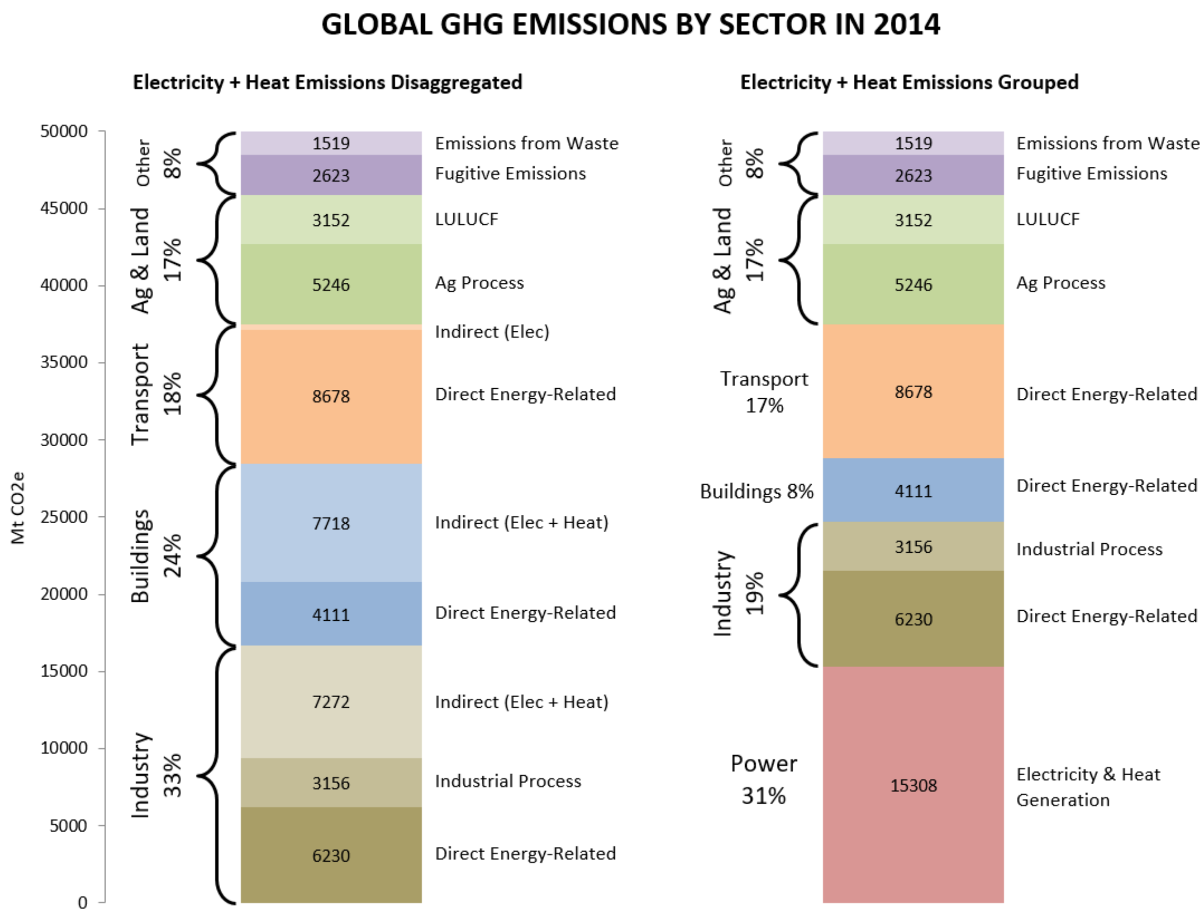
- **Industrial energy efficiency** reduce near-term emissions.
- **less energy intensive process designs, materials, and clean energy technologies** reduce mid-term and long-term emissions.
- **Policies accelerate** reductions

The Shell Sky Scenario (Royal Dutch Shell 2018a) projections from an Integrated Global System Modelling (IGSM) framework

International Energy Agency's (IEA) Energy Technology Perspectives 2017 projections from a technology-rich, bottom-up analytical "backcasting" framework.

Technologies and Policies to Decarbonize the Industrial Sector: Draft Report Table of Contents

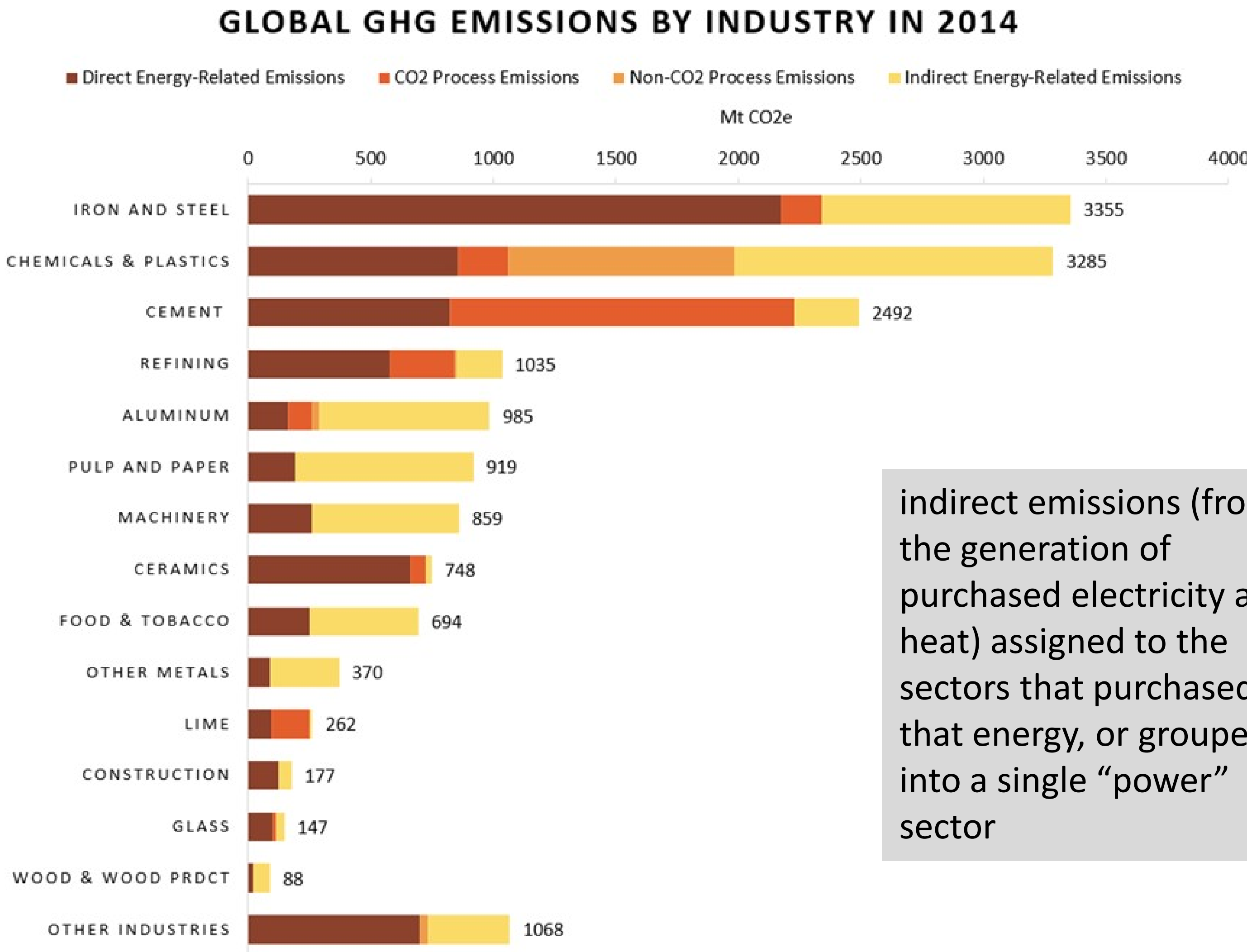
Technologies and Policies to Decarbonize the Industrial Sector: Draft Report Global GHG Emissions by Industry in 2014



- Emissions by sector in 2014, displayed with indirect emissions (from the generation of purchased electricity and heat) assigned to the sectors that purchased that energy, or grouped into a single "power" sector.
- For more detail on which industries are included in the "industry" sector, see next slide.
- Emissions from agriculture, from waste (e.g. landfills, wastewater treatment), and fugitive emissions (e.g. methane leakage from coal mines and natural gas systems) are not considered part of the industry sector in this paper.

Data from (World Resources Institute 2017), (International Energy Agency 2018a)

Technologies and Policies to Decarbonize the Industrial Sector: Draft Report Global GHG Emissions by Industry in 2014



indirect emissions (from the generation of purchased electricity and heat) assigned to the sectors that purchased that energy, or grouped into a single "power" sector

Industry sector GHG emissions disaggregated by industry and by emissions type.