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Decarbonization of the Chemical Industry

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Before Diving In: Here Are Some Facts and Figures About The Chemical Industry

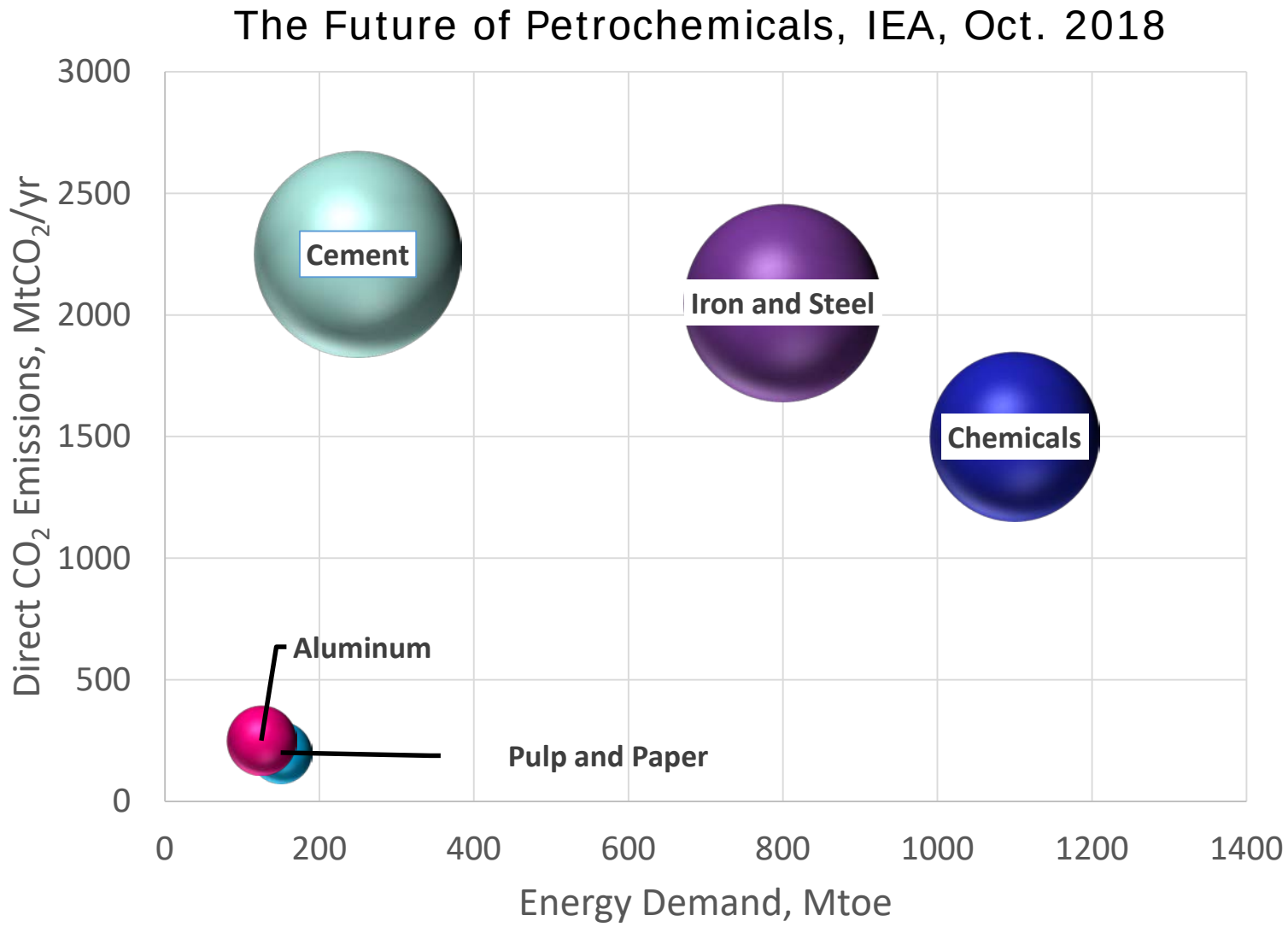
The Chemical Industry Touches Nearly All Goods-Producing Sectors.

In 2017:

- Total gross value $5.7 Trillion = 7% of global GDP
  - $1.1 Trillion directly added to global GDP = ~ GDP of Indonesia
- 120 Million jobs supported = ~ population of Mexico
  - 15 Million directly employed = 14th largest city in the world
- $75,000 gross value add per employee
- $51 Billion in global R&D investment → 1.7 Million jobs

Chemicals Are The Largest Industrial Energy Consumer

Greater Than 50% Is Feedstocks



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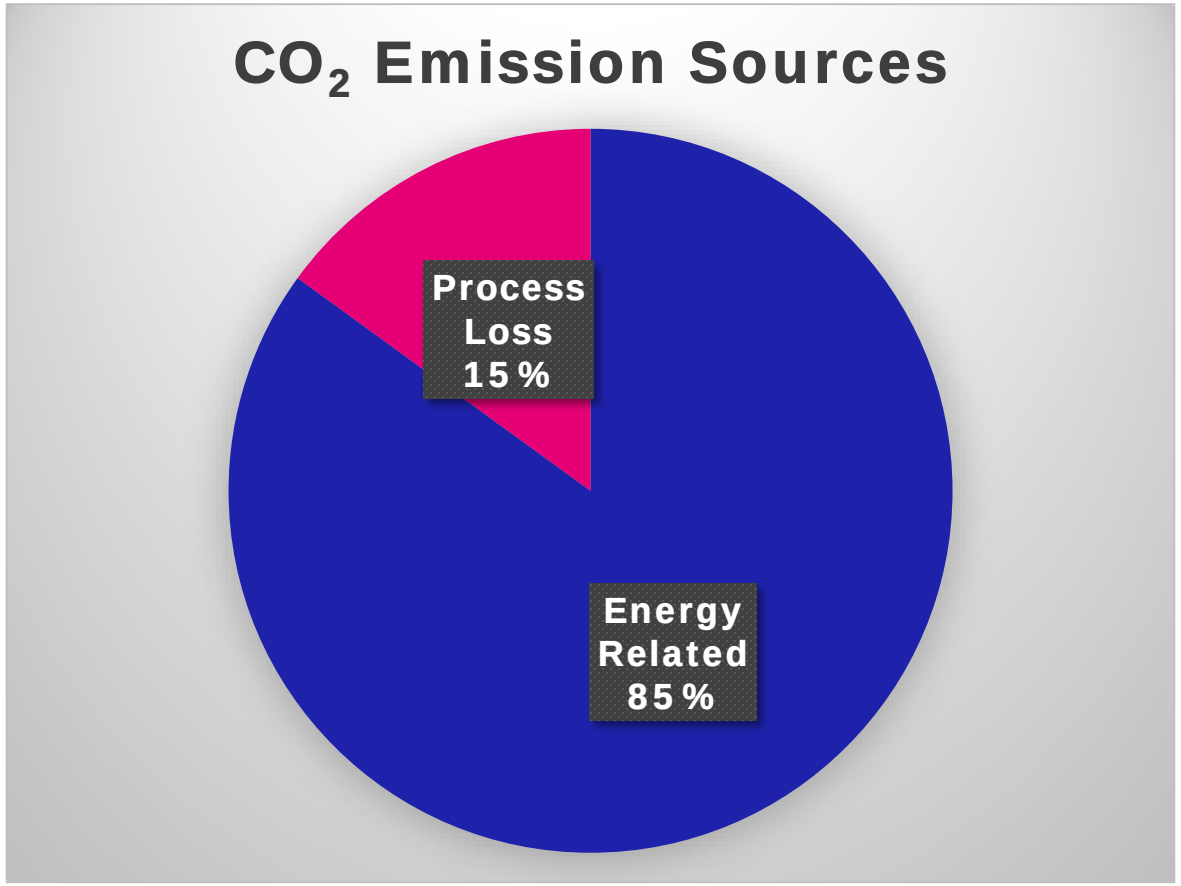
Significant Focus Has Resulted in Highly Optimized Processes



- Between 1977 and 2014, nearly **25%** reduction in non-feedstock energy use
- In 2014, 58% of energy input used as feedstocks
- 1.5 $GtCO_2$ per year – 18% of global industrial CO_2 emissions
- Non-CO_2 GHG emissions are 350 – 400 $MtCO_2$-eq

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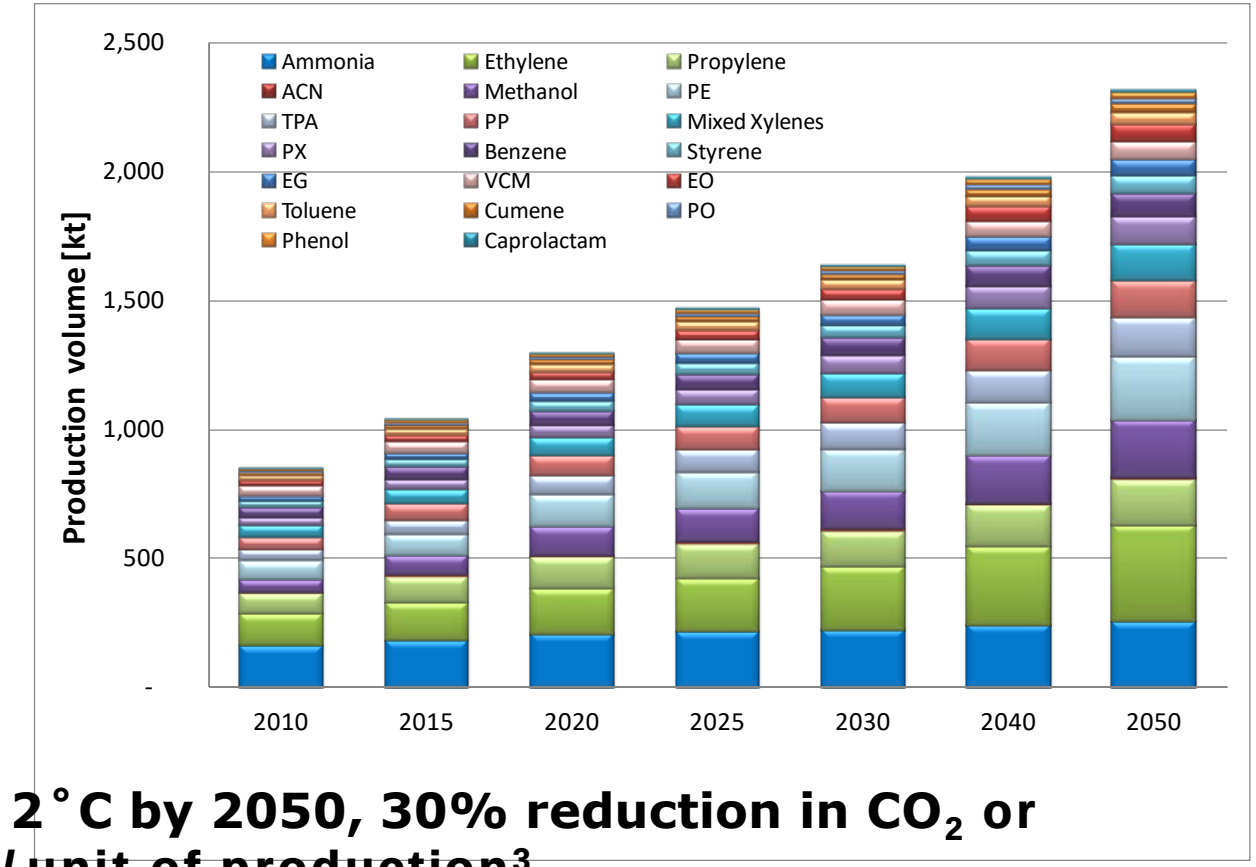
P. G. Levi, J. M. Cullen, Environ. Sci. Technol. 2018, 52, 1725−1734; A. Katelhon, et al, PNAS 2019, 116, 11187' The Future of Petrochemicals, IEA, Oct. 2018

Predictions from Technology Roadmap[1,2] Point Out Need For Different Approaches

Volumes Expected to Grow ~2-3X[1,2]

With no process improvements[1,2] ,

- Energy use to increase by >110%
- GHG emissions to increase by >100%



To give 50% chance of limiting to 2˚C by 2050, 30% reduction in CO_2 or 75% reduction/unit of production[3]

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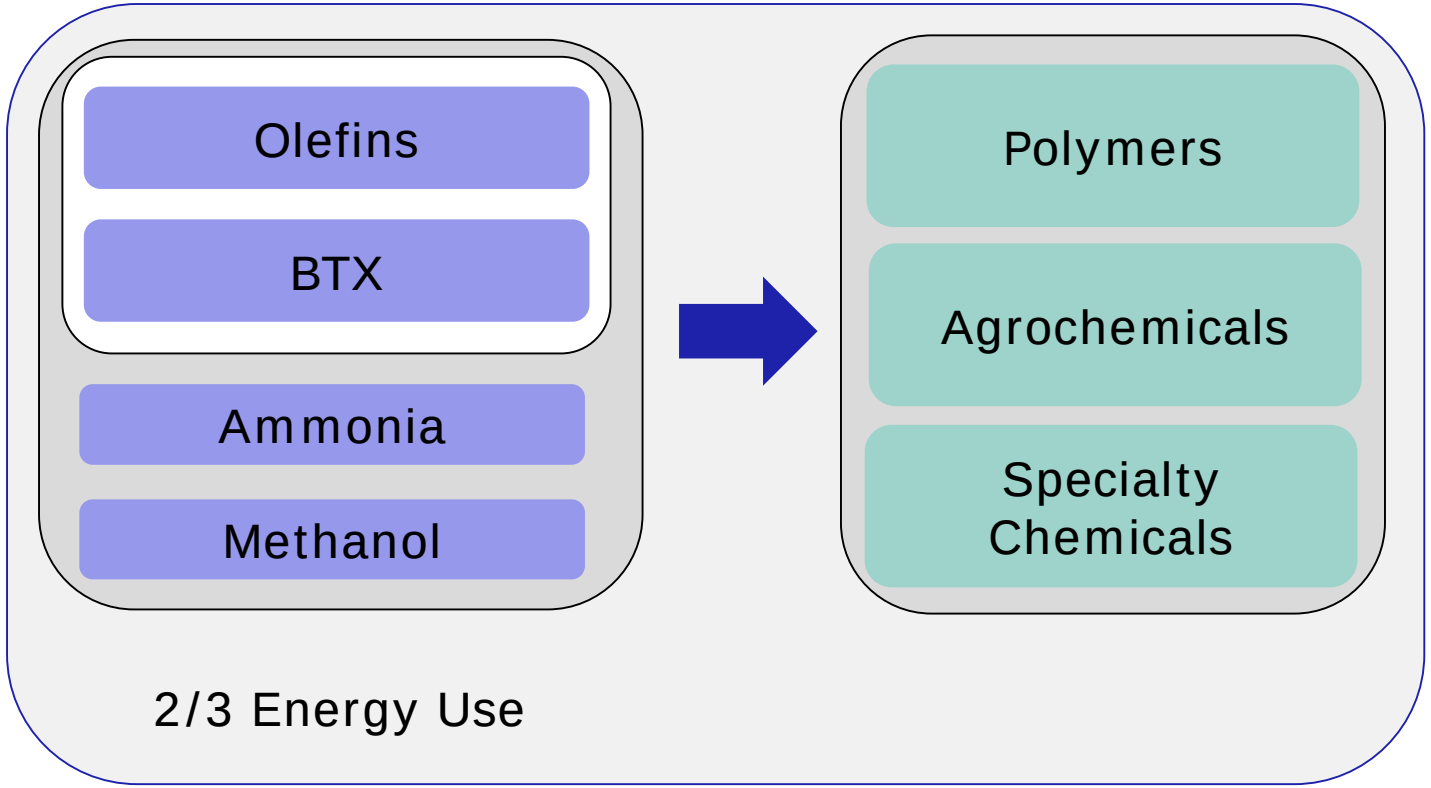
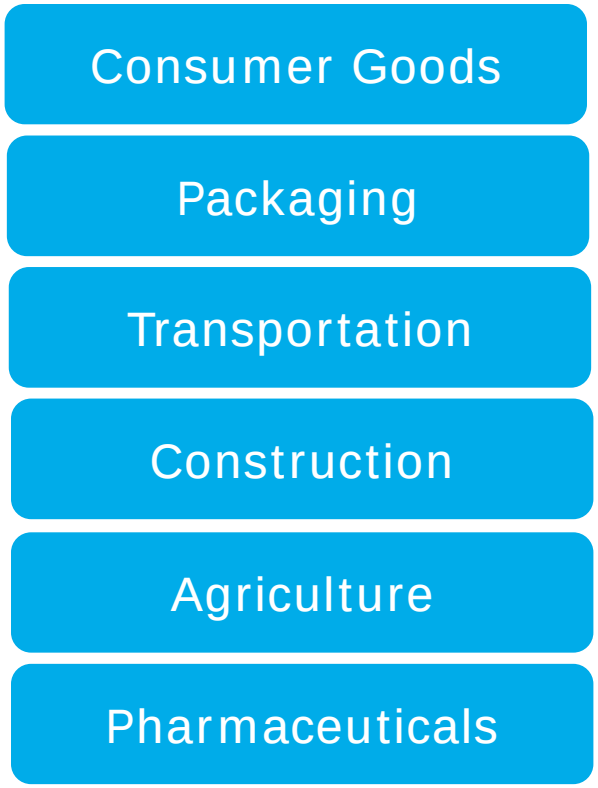
[1]Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes, International Energy Agency, June 2013
[2]https://www.iea.org/publications/freepublications/publication/name,40309,en.html
3P. G. Levi, J. M. Cullen, Environ. Sci. Technol. 2018, 52, 1725−1734

There Are Upstream and Downstream Opportunities to Reduce CO_2 Emissions





- Novel processes/energy optimization
- Alternative feedstock and fuels
- Electrification
- Carbon management (CCS)

- Reduced use: novel materials, new application/forming techniques, improved performance/life, etc.
- Recycling

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P. G. Levi, J. M. Cullen, Environ. Sci. Technol. 2018, 52, 1725−1734; The Future of Petrochemicals, IEA, Oct. 2018

A Variety of Feedstocks And Fuels Are Under Exploration OR In Use

Notable Examples:

- Bioethanol/ethylene in Brazil
- Electrolyzers for H_2
- Coke Oven Gas (off gas from iron and steel) used to generate 20% of methanol in China

Sustainably produced biomass available could supply up to 90 EJ/yr to all of the industrial sector – it can only be a partial solution for the Chemical Industry which used 43 EJ/yr in 2015

Investment Is Needed

- Venture capital investments in clean tech sector have decreased dramatically since 2011
- Biomass conversion investments have dropped since 2015
- Equipment costs for handling biomass ~7X more expensive

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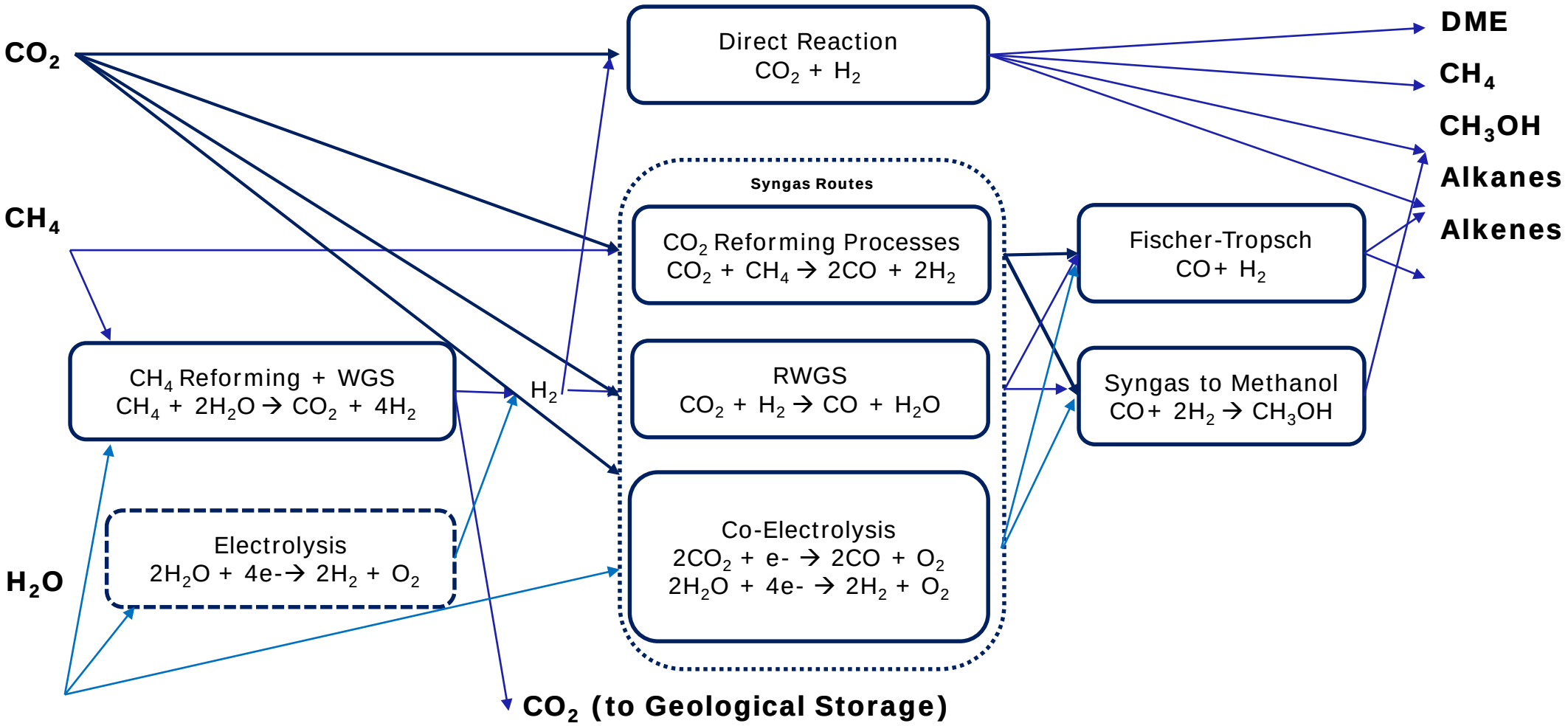
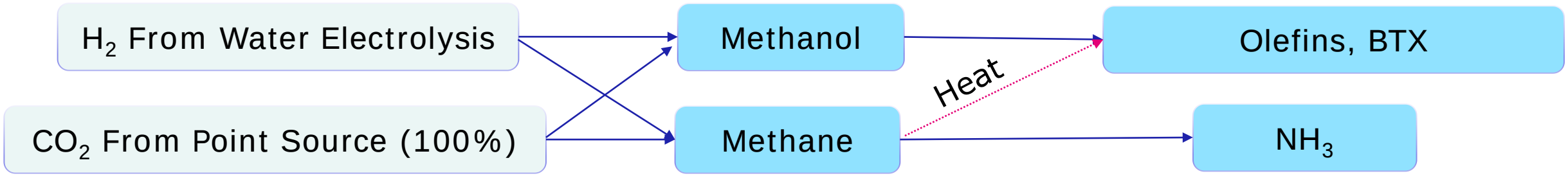
The Future of Petrochemicals, IEA, Oct. 2018; Decarbonization of industrial sectors: the next frontier, McKinsey & Company, June 2018

New Feedstocks Are Being Proposed For Commodity Chemicals



Adapted from Carbon Dioxide Utilization (CO2U) ICEF Roadmap 2.0, Nov. 2017

One CCU Model Explored Highlights The Complexity



Results:

- Mass flows increased by 287% → **larger plants will be required or significant intensification will need to be developed**
- 32 PWh of electricity needed → **97% of projected world electricity supply by 2030**
- If all additional electricity were renewable, **222% of targeted installation would be required**
- If oil is $92.3/barrel, electricity is $1.8 – 3.5 kg/$H_2$, **additional operating costs would be $564-1,570 billion annually**
- The additional costs would be **59-164% of 2017 market value** for these 20 chemicals
- Costs for CO_2 reduction would be **$168-467/t CO_2 equivalent**

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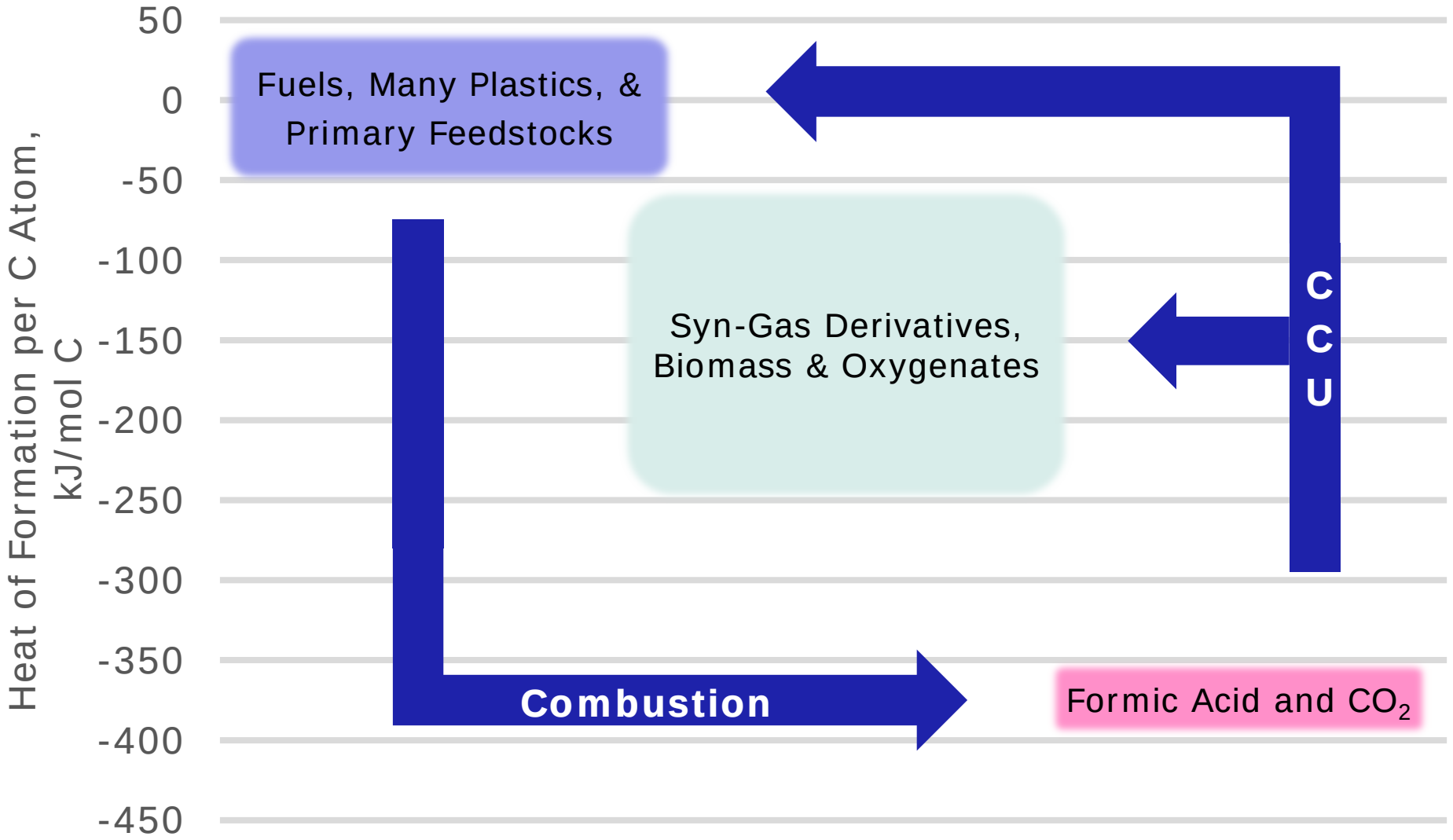
A. Katelhon, et al. PNAS 2019, 116, 11187

CCU Thermodynamics Are Challenging



Adapted from M. Bender, et al., Chem. Ing. Tech. 2018, 60, 1.

Opportunities for CCU Exist

Carbon Recycling International's Vulcanol™: 4,000 metric ton/year MeOH with CO_2 from flue gas of geothermal power plant:

- Availability of low cost electricity for generating H_2 via electrolysis
- High CO_2 concentration (85-90%) from geothermal powerplant
- EU requirement for sustainable feedstocks in liquid fuels like methanol

Agreement signed in May 2019 with Henan Shuncheng Group for a 180 kta/year methanol and LNG facility using CO_2 feedstock

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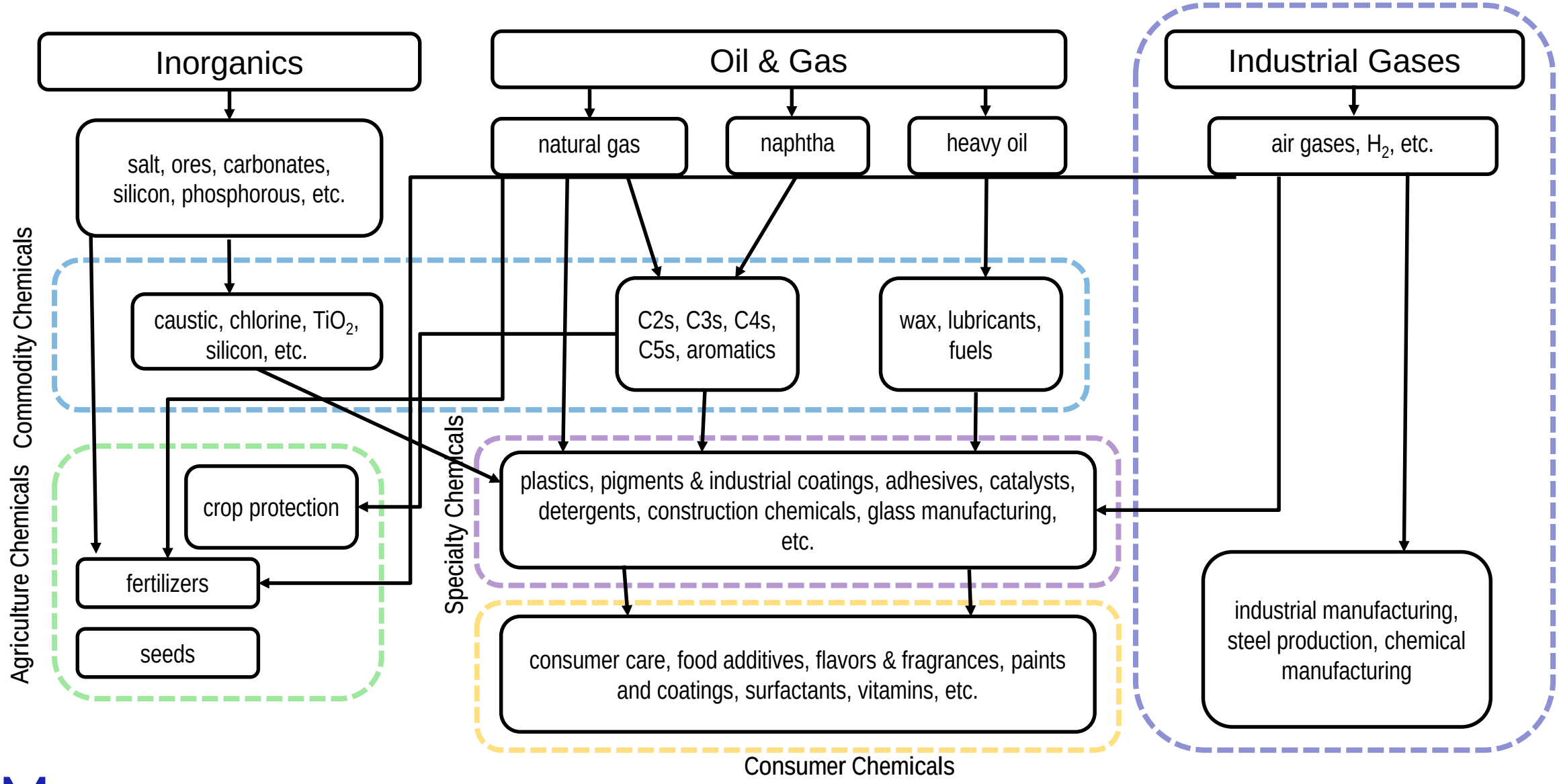
www.carbolrecycling.is, accessed July 21,2019, Gaseous Carbon Waste Streams Utilization Status and Research Needs, NAS, 2019

Integration and Scale Add Complexity & Opportunity



Adapted from The Chemical Industry Reimagined, EY, 2018

Need For Integration Consideration Evident In An Ethylene Cracker Electrification Example

Ethylene production generates 0.2 GT CO_2/year or ~10% CO_2 of the chemical industry from fuel for the furnaces

Currently no commercial high temperature electric furnaces are available

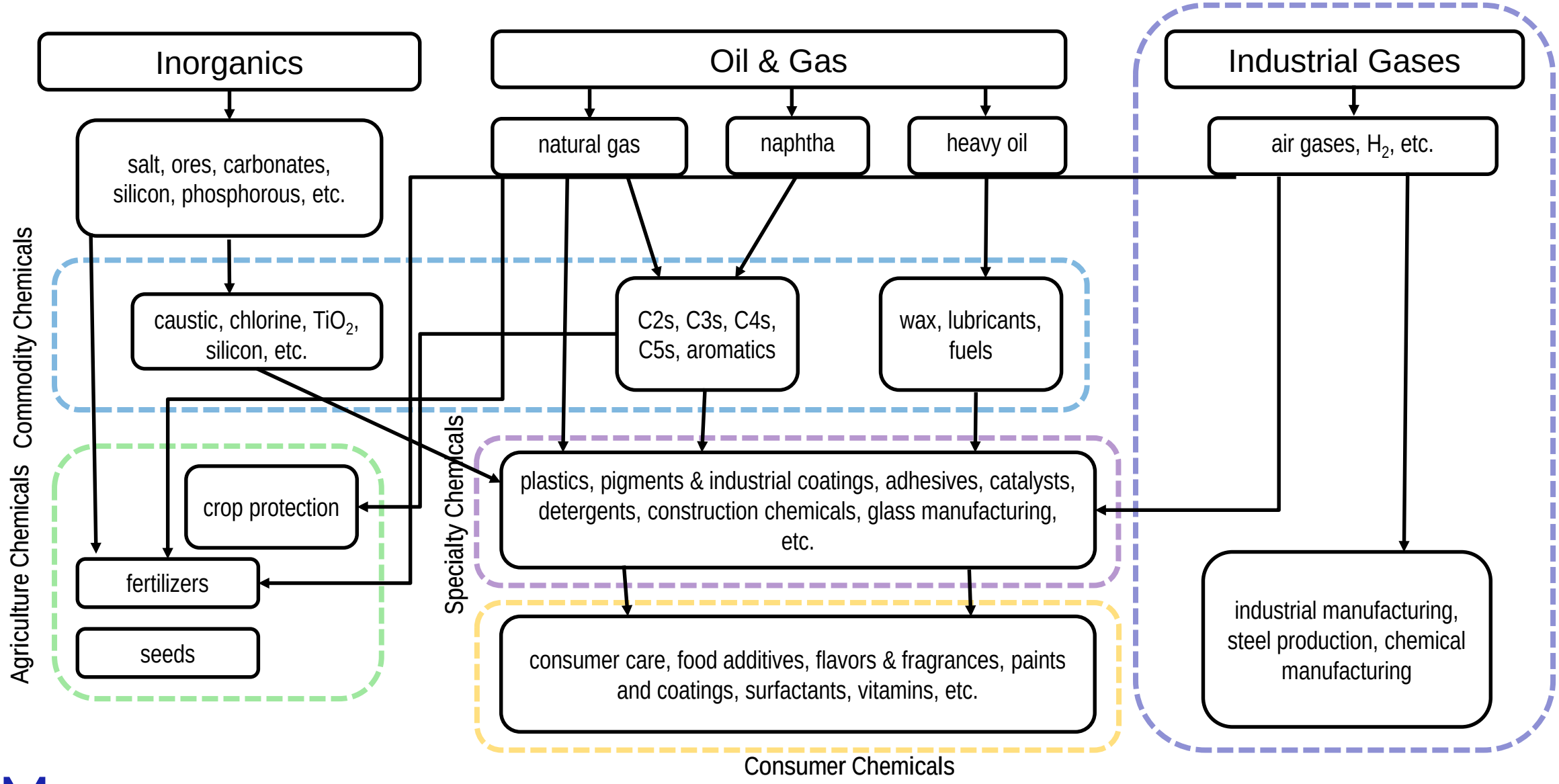
- Expected to be more efficient than current combustion
- Less heat available for downstream processes, so they would need to be electrified as well

McKinsey & Company 2018 estimates:

- $25/MWh renewable electricity needed for greenfield ethylene plant electrification
- $15/MWh renewable electricity needed for brownfield ethylene plant electrification

For electrification to be cost-competitive to using CCS for CO_2 management

Current Infrastructure Build Out Adds To The Complexity



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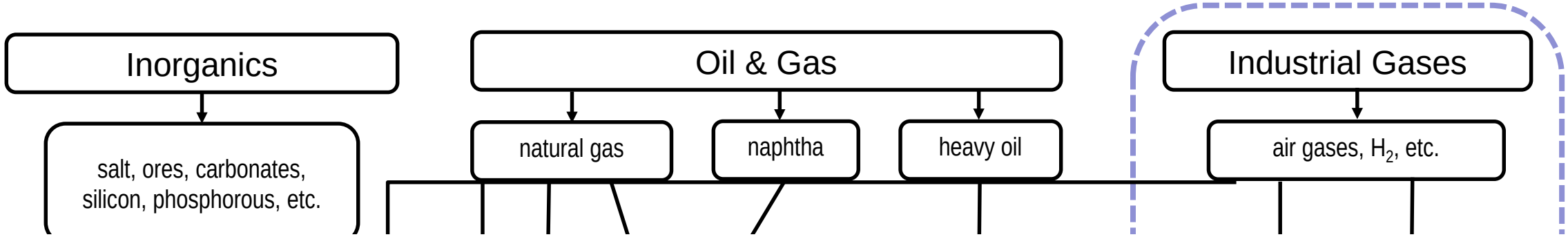
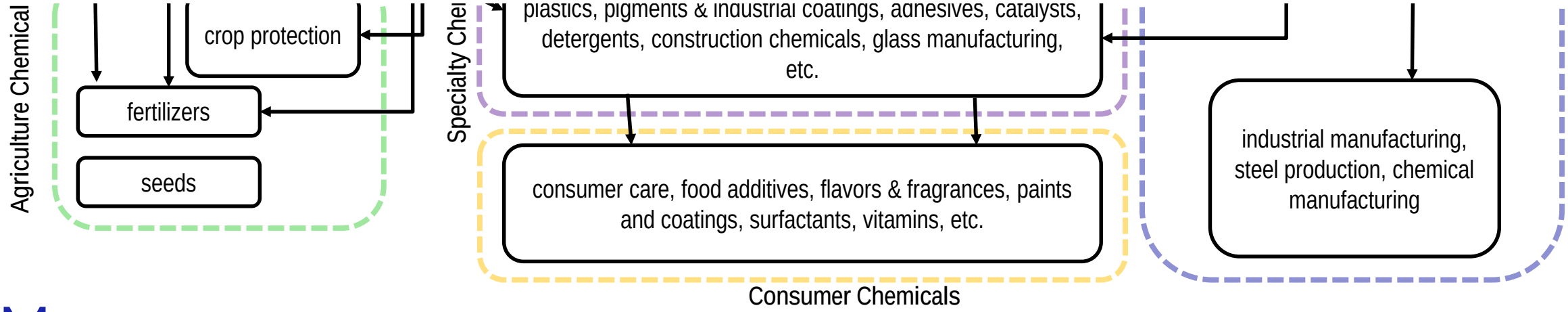


“The biggest obstacle to innovation is a paid off plant.” –From the Innovation Abyss by Chris DeArmitt



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Adapted from The Chemical Industry Reimagined, EY, 2018

Decarbonization Is Possible

Technology development is needed to improve economics

Final solution will require multiple approaches

Willingness/ability to absorb additional costs will be important

Investment needs to be harmonized across industry and coordinate across sectors

Regulatory push and/or subsidies may accelerate transition

In science the credit goes to the man who convinces the world, not the man to whom the idea first occurs. -- Sir Francis Darwin

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